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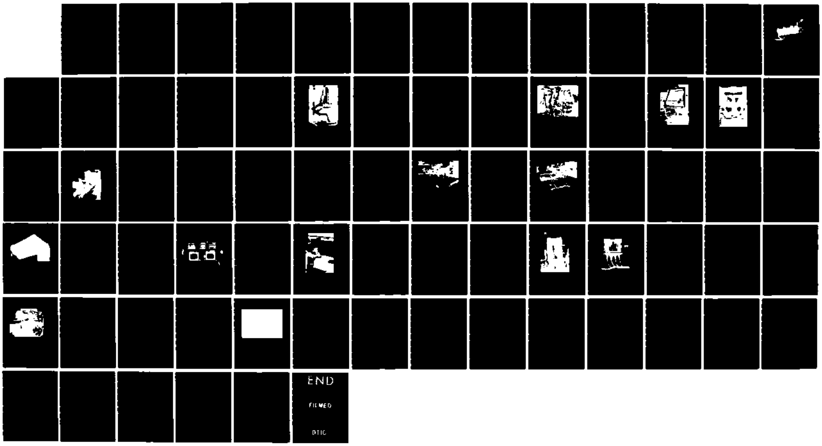

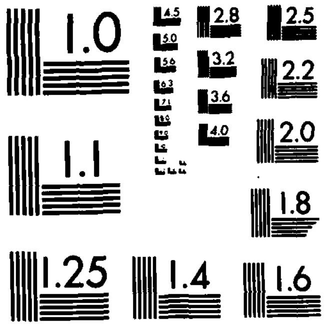

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Final Report

AN EXPERIMENTAL STUDY OF AN ULTRA-MOBILE VEHICLE FOR OFF-ROAD TRANSPORTATION

Robert B. McGhee and Kenneth J. Waldron
College of Engineering

For the Period
October 1, 1981 - September 30, 1984

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
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* AN EXPERIMENTAL SUTDY OF AN ULTRA-MOBILE VEHICLE FOR OFF-ROAD TRANSPORTATION

This report provides a summary of research results obtained at Ohio State University under DARPA Contract MDA903-82-K-0058 during the three year period extending from October 1, 1981 through September 30, 1984. This research was concerned with the design and construction of an experimental six-legged vehicle for off-road transportation called the Adaptive Suspension Vehicle (ASV). The research was organized into three phases, corresponding to the three project funding years (FY 82, 83, and 84). The introductory section of this report provides a brief overview of research accomplished during each of these years. Subsequent sections provide more detailed information regarding major research findings in the areas of mechanical engineering and electrical engineering respectively. The report concludes with an overall summary, a list of

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publications, and a separately-bound appendix providing details of the geometry and limb coordination principles of the ASV system under construction at the completion of this contract. The latter work is currently supported by DARPA under Contract DAAE07-84-R001, which is the successor to Contract MDA903-82-K-0058.

Mechanical and electronic design of the ASV was driven by the following primary goals relating to vehicle performance:

1. The vehicle should be able to traverse a significant variety of terrain not negotiable by conventional wheeled or tracked machines.

2. The interior payload capacity should be at least 500 lb.

3. The vehicle should exhibit a cruising speed of 5 mph. and a top speed of 8 mph. in off-road locomotion.

4. The vehicle should carry its own prime mover and computer.

5. Provision should be made for a human driver to steer the vehicle by interaction with the on-board computer at a supervisory control level.

6. The vehicle should possess a vision system with sufficient capability to permit automatic selection of footholds without human intervention. and

7. The overall size and weight of the ASV should be comparable to that of a small truck or light helicopter.

The final vehicle configuration described in this report achieves all of the above design goals. The completed machine is approximately 10 ft. high, 7 ft. wide, and 17 ft. long. Total system weight is roughly 6,000 lb., including the driver and payload. Testing of the completed vehicle will begin in June of 1985.

While the ASV is a proof-of-concept vehicle, and not an operational prototype, it is anticipated that it will play an important role in experiments to be conducted in support of a design study of a more advanced legged vehicle called the Agile Autonomous Vehicle (AAV). The AAV is expected to exhibit higher speed, smaller size, and greater agility in comparison to the ASV, and will represent a further step toward the realization of a new class of military vehicles with entirely unique mobility characteristics. Conceptual design of the AAV is now under way at Ohio State University under DARPA Contract DAAE07-84-K-R001.

Final Technical Report

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DARPA Contract MDA903-82-K-0058

AN EXPERIMENTAL STUDY OF AN ULTRA-MOBILE VEHICLE FOR OFF-ROAD TRANSPORTATION

Prepared by

Robert B. McGhee and Kenneth J. Waldron

covering the period

October 1, 1981, through September 30, 1984

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The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

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1. INTRODUCTION

This report provides a summary of research results obtained at Ohio State University (OSU) under DARPA Contract MDA903-82-K-0058 during the three year period extending from October 1, 1981 through September 30, 1984. This research was concerned with the design and construction of an experimental six-legged vehicle for off-road transportation called the Adaptive Suspension Vehicle (ASV). The research was organized into three phases, corresponding to the three project funding years (FY 82, 83, and 84). This section of this report provides a brief overview of research accomplished during each of these years. Subsequent sections provide more detailed information regarding major research findings in the areas of mechanical engineering and electrical engineering respectively. The report concludes with an overall summary, a list of publications, and a separately-bound appendix providing details of the geometry and limb coordination principles of the ASV system under construction at the completion of this contract. The latter work is currently supported by DARPA under Contract DAAE07-84-K-R001, which is the successor to Contract MDA903-82-K-0058.

1.1 First Year Research Summary

During the first year of research under this contract (FY82), project activities were concentrated on preliminary design of the ASV system and on the identification of possible components for this vehicle. Early in the project, the vehicle name was changed from the Ultra-Mobile Vehicle (UMV) to the Adaptive Suspension Vehicle, to emphasize its ability to actively adjust the geometrical relationship between its body and its supporting elements. Although it was assumed, from the beginning, that the ASV would be a walking machine, it was also recognized that many of the sensing and control techniques to be developed would be applicable as well to advanced wheeled or tracked vehicles. The change in the vehicle name was further motivated by a desire to indicate this feature of the research program.

Because of the exploratory nature of the first year of research, two subcontracts were let to foreign research organizations in an effort to ensure adequate access to the world-wide knowledge base relating to advanced off-road mobility concepts. The first of these was to Mr. J. Vertut of CEA, Saclay, France (French Atomic Energy Commission). Mr. Vertut was at that time, and remains, an acknowledged leader in research in the field of manipulators and mobility systems for robots and teleoperators designed for operation in hazardous environments and difficult terrain. The second subcontract was to Prof. Keir Pearson, of the University of Alberta, Edmonton, Alberta, for a study of the gaits of insects during turning maneuvers and in overcoming large obstacles. Finally, per contract provisions, Prof. Shigeo Hirose of Tokyo Institute of Technology spent two months at OSU assisting in the preliminary design of the ASV leg geometry. The final choice of a planar pantograph leg was partially due to his experience with pantograph walking machine leg mechanisms.

By the end of the first year's work, conceptual design of the ASV was completed and preliminary specifications for all major subsystems as well as for the vehicle operational software were determined. In the course of this work, several experimental laboratory-scale walking vehicles were constructed and tested. Details concerning these machines can be found in the following sections of this report and in publications in the open literature listed in the attached Appendix 1.

1.2 Second Year Research Summary

The second year of this project (FY83) was devoted to further configuring of the overall ASV system, to component evaluation, and to construction and testing of certain major subsystems. In particular, a flywheel energy-storage system was constructed by the University of Wisconsin to specifications determined by OSU. In addition, an optical terrain-scanner and an associated vehicle guidance computer were designed and constructed by the Environmental Research Institute of Michigan (ERIM) in cooperation with Battelle Columbus Laboratories. Specifications for both of these subsystems were developed in consultation with OSU.

Major research accomplishments at OSU included the design and construction of a prototype vehicle leg. This system was used for the experimental investigation of several different hydraulic actuation configurations for the ASV, and to verify the mechanical design of the leg mechanism. The principal result of these studies was that it is possible and desirable to provide one variable-displacement hydraulic pump for each of the eighteen joint actuators of the ASV. This approach avoids the energy losses found in conventional hydraulic systems which result from throttling of oil flow to each actuator from a common pressure-regulated supply. Conservative calculation of the anticipated energy requirements associated with the one-pump-per-actuator design concept indicated that 70 hp. represented an upper bound for operation of the ASV at its designed top speed of 8 mph. Accordingly, a 900 cc. Kawasaki motorcycle engine was selected as the vehicle prime mover. Also during this research year, fabrication and testing of the vehicle frame was completed. In conjunction with this activity, it was decided that an earlier integral operator's compartment concept provided inadequate space, and a separate modular cab configuration was adopted instead. This decision increased the length of the ASV body by about 20 percent over the original design concept.

With respect to electrical system research, construction of a breadboard version of the ASV control computer was completed during the second research year. This system was composed of nine Intel 86/30 single-board computers consisting of six leg control computers, one cockpit communication computer, a coordination computer, and a safety computer, all connected to a common Intel Multibus. Upon completion of this computer, an intensive software development effort was undertaken to realize a set of six distinct vehicle operational modes defined during the first year of research. Of equal importance, work was begun on a real-time operating system designed to efficiently coordinate the activities of all nine computers in the vehicle control system. The overall software development effort was facilitated by continuing experiments with a laboratory-scale walking machine, the OSU Hexapod. During this research year, the latter machine was used to demonstrate for the first time in any research program the successful integration of operator inputs, inertial sensing, optical ranging, proprioceptive sensing, force sensing, and proximity sensing in the control of a walking vehicle. While this work made use of a uniprocessor computer (DEC PDP-11/70), the algorithms validated in this way were subsequently adapted to control of the ASV.

In summary, by the end of the second year of research, the overall configuration of the ASV was essentially frozen. Figure 1 is a photograph of a model showing the general appearance of the resulting system. In addition, during this year, the construction of several major subsystems was completed and others were well under way. Per the original project plan, third year

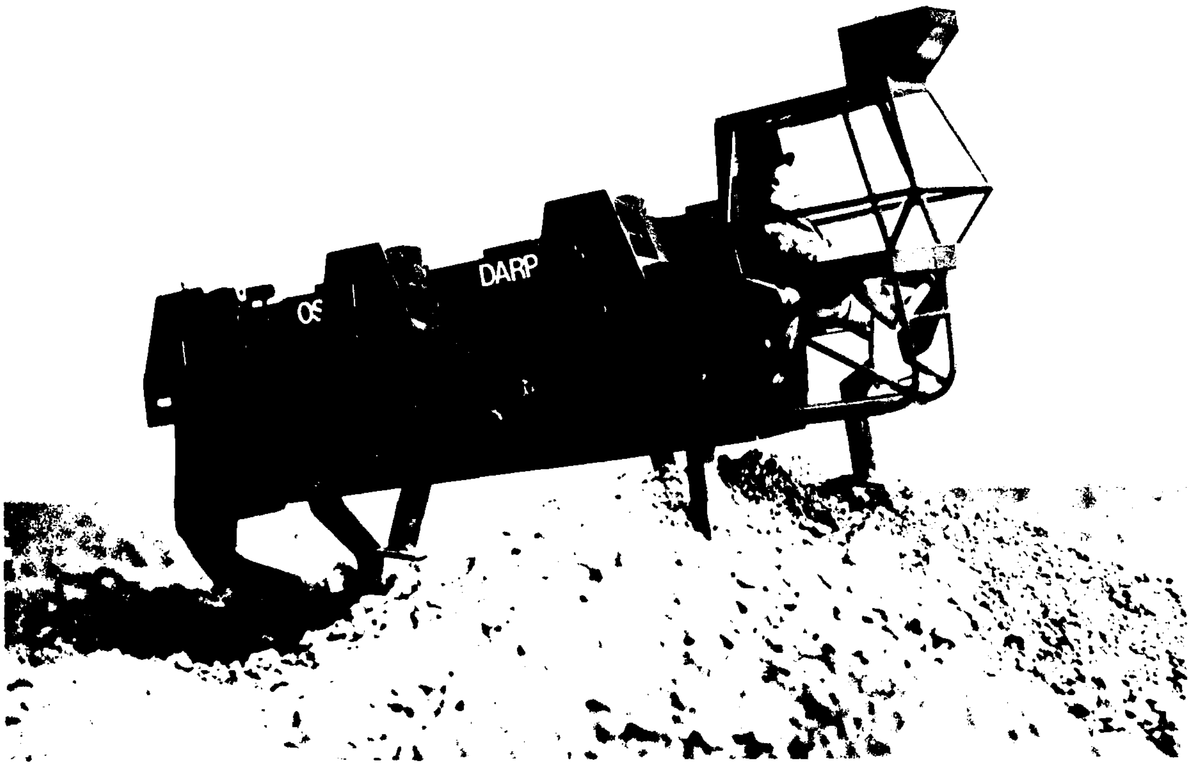

Figure 1. Scale model of ASV on terrain board. Length of full-size system = 17 ft., width = 7.5 ft., nominal height at back = 8 ft. Total weight is 6,000 lb. including driver, optical terrain scanner mounted on top of cab, fuel and fluids, and 500 lb. payload in internal cargo bay.

speeds up to 12,000 rpm. Operating in the range between 6,000 and 12,000 rpm it stores up to 0.5 hp. hour of recoverable energy. Even at minimum speed, it retains approximately 0.125 hp hour. This is enough for 10-15 sec. of vehicle operation at the 40 hp level expected in average circumstances. This time is adequate for emergency landing and system shutdown.

As of the time of this writing, the flywheel shown in Fig. 5 has been successfully operated at 10,000 rpm. An improved flywheel has been tested to 14,000 rpm., but a minor failure occured at that speed. Specifically, a small portion of the titanium spool on which the rim is wound separated, causing the wheel to become unbalanced and separate from the quill on which it was being tested. The wheel maintained its integrity, and it is anticipated that this problem will be solved by a change in manufacturing procedures.

It is expected that the final version of the flywheel will be capable of operation at the full design speed of 12,000 rpm with a comfortable margin of safety. Delivery of such a flywheel by the University of Wisconsin and subsequent installation by OSU is planned prior to outdoor testing of the ASV. Until then, the current flywheel is felt to be satisfactory for indoor testing.

As mentioned above, the use of a large flywheel provides other benefits to the ASV. In particular, because the total hydraulic horsepower needed for locomotion may involve large peaks during obstacle negotiation, rapid acceleration, etc., it would be necessary to choose an engine capable of handling peak demands if the flywheel were not used. This would greatly increase engine bulk and would somewhat increase fuel consumption. With a flywheel, the engine need deliver only the <u>average</u> power needed for locomotion. This being the case, it was possible to select a light-weight 900 cc.

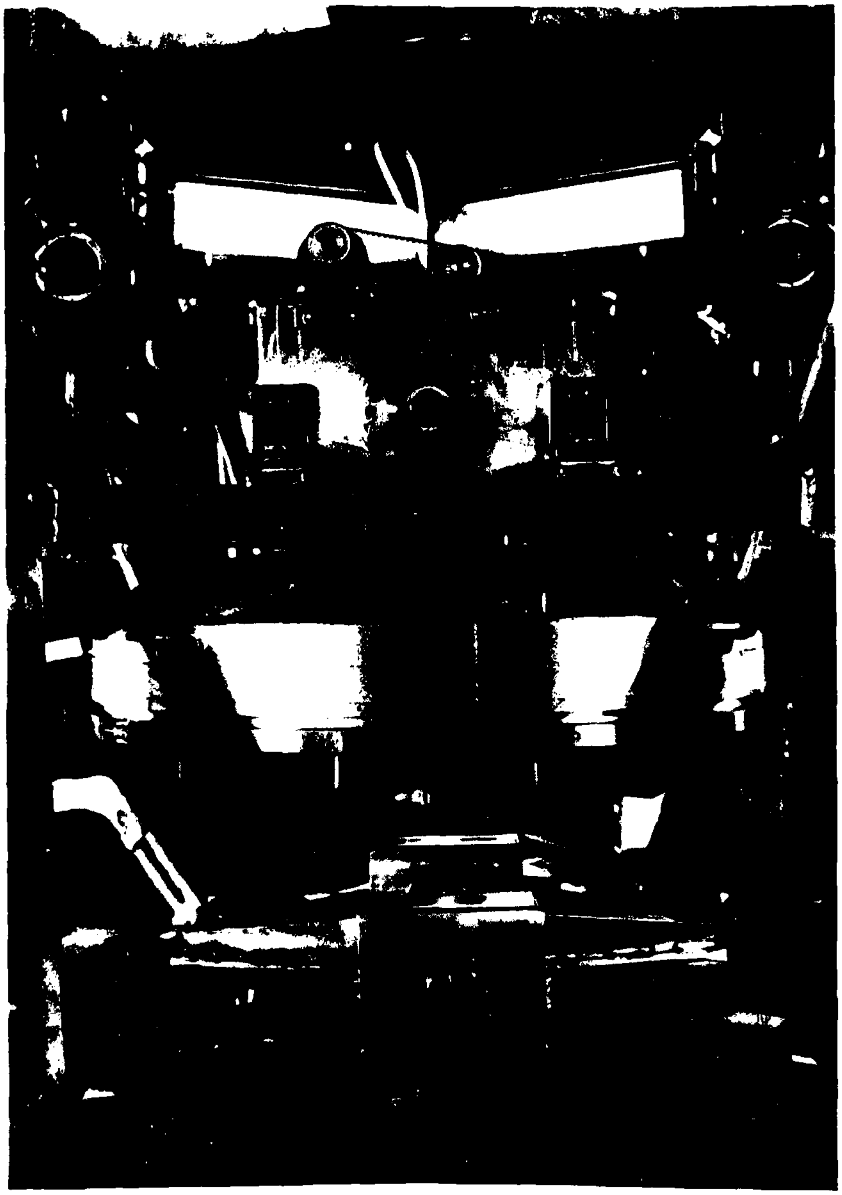

Figure 5. ASV flywheel assembly mounted in vehicle frame. Case diameter is 25 inches, total weight is 210 lbs.

Figure 4. Dismounted ASV cab showing keyboard, displays, and hand-controller.

as much work-space as possible. On the other hand, operator safety requires a rugged structure capable of surviving a crash at maximum vehicle speed. This consideration results in unacceptable weight penalties for a large cab. Figure 4 shows the cab configuration resulting from a tradeoff of these criteria. This figure also shows the hand-controller and operator's displays. These items will be discussed further in a following section of this report dealing with electrical system research.

2.4 Prime Mover and Power Train

Because the ASV is actively supported by hydraulic pressure in its lift cylinders, the role of the system prime mover is unlike that of a conventional land vehicle in which engine failure merely results in a loss of forward motion capability. Instead, the prime mover function is essentially the same as in an aircraft in which engine failure produces an inability to maintain altitude. For this reason, it is important that some means be provided for a controlled shutdown in which the ASV can settle onto attached belly skids under computer control. Execution of such a maneuver requires that sufficient energy be stored someplace in the vehicle system. Energy storage is also required to permit regenerative braking using the hydrostatic actuation system, to permit high power densities to be drawn to meet short term demands, and to allow the engine to be isolated from the very strong drive-line torque fluctuations produced by the locomotion system. As part of the previously referenced one-year design study, both flywheel and accumulator storage systems were investigated for this purpose. The greater energy density of storage per unit weight or volume lead to the choice of a flywheel system. A suitable flywheel was subsequently designed and delivered by the University of Wisconsin. This flywheel, shown in Fig. 5, is designed for operation at

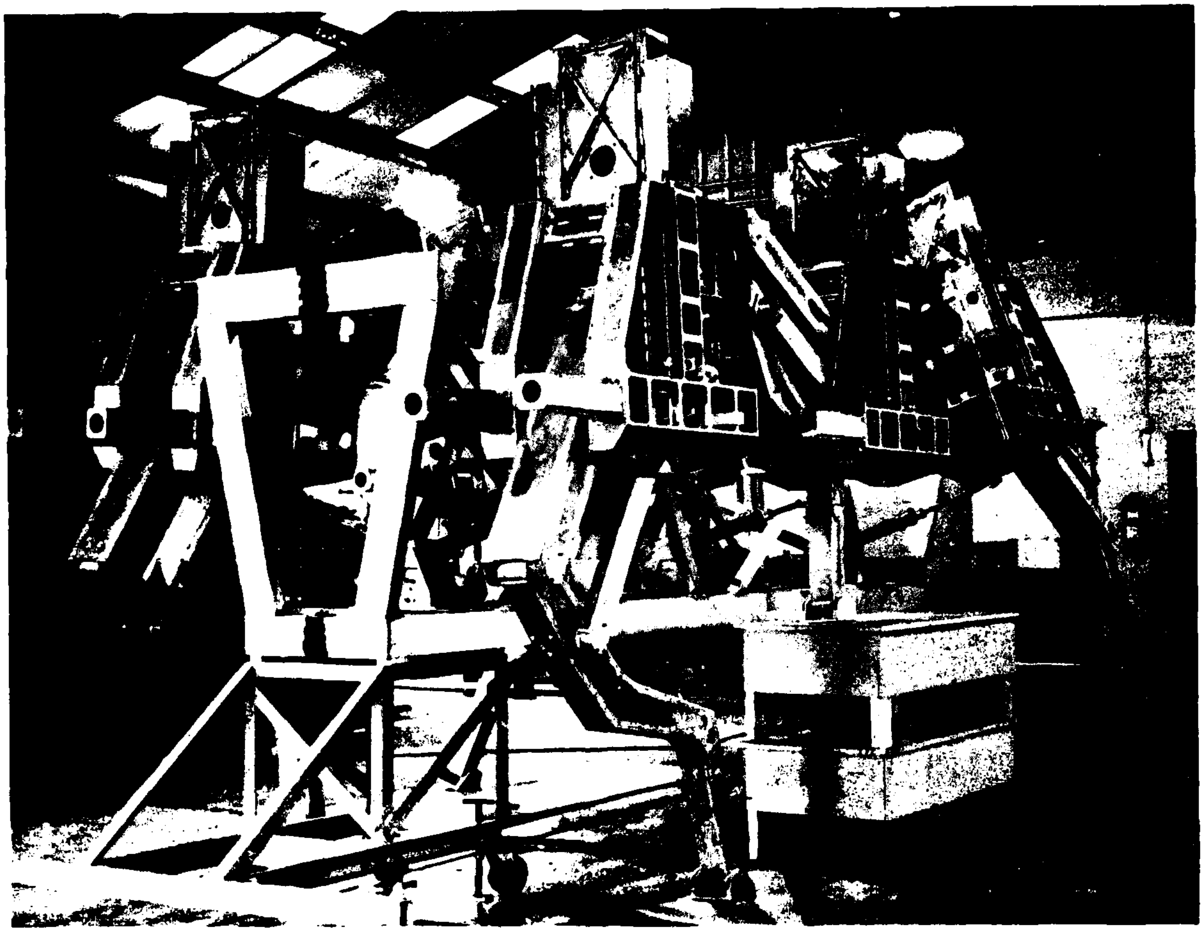

Figure 3. Partially assembled ASV system showing range of motion of legs.

force sensing of leg/terrain interaction [41,49,52,53,54]. Energy tests with this leg indicate that locomotion at the design top speed of 8 mph. should be possible with a continuous input of 50 hp. from the ASV prime mover, well within the 70 hp. available. It is worth noting that each leg of the ASV amounts to an extremely powerful and fast three-degree-of-freedom manipulator with a lift capacity in excess of 3,000 lbs. and a maximum velocity at the foot of 12 ft./sec.

2.3 Structure Design

Since the ASV legs provide both lift and propulsion, they are evidently the pacing items in structural design. However, designing a suitable frame to interconnect the legs and carry both the electronic systems and the prime mover system was also a challenging task [37,38]. One of the first problems was to find an approach to frame design which would permit the legs to be mounted so as to allow their full range of motion to be utilized without interference while keeping both weight and physical size to a minimum. At the same time, it was felt that it was very important to provide good accessibility for ease of modification of subsystems. A space-frame approach using welded aluminum box beams as the basic structural element was therefore selected for the ASV frame design. After extensive finite element design studies [30], the frame was constructed [21] and subsequently passed all static and dynamic loading tests. Figure 3 shows the completed frame with legs attached. As can be seen, the frame is narrower at the bottom than at the top so as to allow a greater range of motion in moving the legs of the vehicle toward the center of the body.

The design of a modular cab structure for the ASV also involved conflicting criteria. Evidently, it is desirable to provide the operator with variable hydrostatic power transmission system [38]. At any instant of time, the flow rate of this system is determined by a conventional valve-controlled rotary actuator in which the output shaft angle determines the swash-plate angle of the associated variable displacement pump. As described in [38,44, 57], these rotary actuators are all supplied from a common pressure-compensated source. Thus, overall, the ASV hydraulic system uses nineteen pumps, eighteen servo-valves, eighteen rotary actuators, and eighteen linear actuators. These items, together with the associated tubing, filters, reservoirs, and other miscellaneous hydraulic components, account for approximately one-third of the total ASV system weight.

In addition to the basic hydraulic actuator system described above, the ASV employs two other hydraulic subsystems. One of these is a passive hydraulic system which maintains the sole of the foot of each leg approximately parallel to the body to provide a controlled contact angle at touch-down. Figure 7.11 of Appendix 2 describes the operation of this system. The other subsystem is comprised of eighteen explosively-actuated safety valves associated with the actuators of each leg. Firing of any one of these valves disables the corresponding actuator by introducing a throttled bypass circuit. When this has been done, the affected actuator is thereby reduced to a hydraulic damper. The logic involved in implementing computer firing of the safety valves is extremely complex and is the subject of continuing research [57,59].

Feedback control of joint actuators is accomplished by the on-board ASV control computer. This computer allocates one Intel 86/30 single-board computer to this function for each leg. Fully satisfactory operation of this system has been demonstrated with the prototype leg using both proximity and

2.2 Leg Actuation

In the design study preceding the subject contract, it was concluded that only hydraulic actuators could provide adequate force and speed capabilities in the weight range acceptable for the ASV. Considerable effort was therefore expended under this contract to arrive at a lightweight and efficient hydraulic actuation scheme. Initially, commercial hydraulic cylinders were purchased and installed in a hydraulic test-bed fixture to evaluate various combinations of series and parallel actuator connections [9,10,19,28]. These tests were motivated by a desire to minimize the number of independent hydraulic pumps in the ASV, thereby reducing cost and weight. In the end, none of these schemes proved attractive. In particular, in every case, series connection of actuators produced poor controllability, while parallel connection resulted in excessive wastage of energy. The final solution, illustrated by Fig. 6.15 of Appendix 2, was actually a return to a concept considered early in the design study and abandoned because other concepts seemed to offer lighter weight and faster response. This system is configured as a hydrostatic system. That is, it is based on direct control of hydraulic fluid flow to each actuator and therefore requires one variable-displacement pump for each of the eighteen joints of the ASV [16,19]. As described in [37,59], mechanical power is distributed to each such pump by a gear belt driven by one of three line-shafts running down each side as well as through the belly of the ASV frame.

A more detailed examination of the ASV hydraulic system reveals that the use of a variable-displacement pump connected to the specially designed constant-volume ASV joint actuators amounts to an efficient continuously-

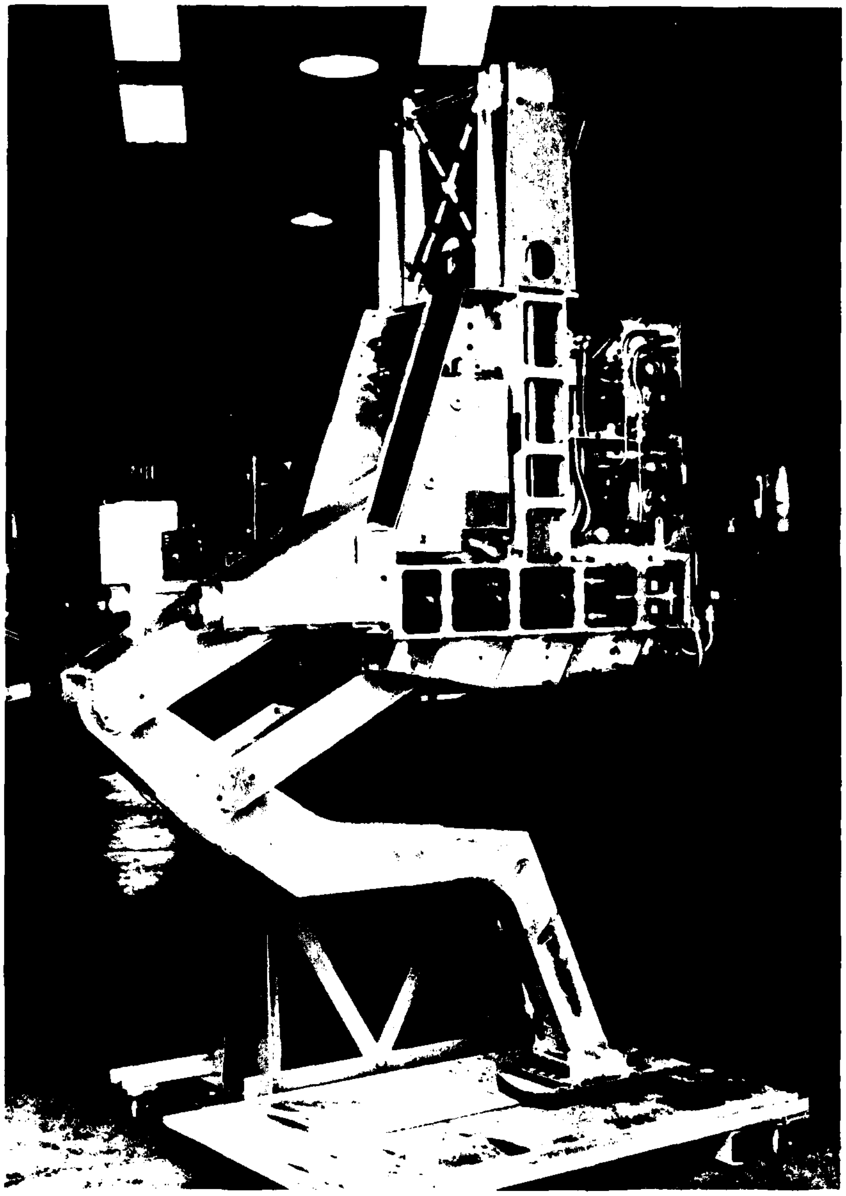

Figure 2. ASV leg on assembly stand. Cover plate has been removed to show internal structure and hydraulic components.

stroke until the appropriate moment to interchange legs, when the latch was released by a solenoid. Because each leg functioned as a free pendulum during swing phase, allowing efficient exchange of kinetic and potential energy, and because all coordination was mechanical, thereby eliminating actuator frictional losses, the DUWE exhibited a specfic resistance of only 0.05. That is, it was capable of "gliding" down a ramp with a 20:1 slope. This performance is comparable to that of wheeled vehicles, and served to demonstrate that, from the point of view of energy requirements, there is no intrinsic inferiority of legs relative to wheels for mechanical forms of locomotion [60].

Despite the above positive results, the four-bar linkage leg geometry was abandoned when it became apparent that the mechanical design of a full-scale leg based on this geometry would present serious problems. In order to obtain sufficent vertical travel capability, a large sliding joint located in the lower leg would have been necessary. The satisfactory design of this joint was the major difficulty with this concept. Instead, a planar pantograph leg geometry was found to represent the best design compromise to meet the conflicting requirements of light weight, strength, and gravitational decoupling. Figure 6.21 in Appendix 2 shows the resulting prototype leg. Figure 6.14 shows how the three degrees of freedom of this leg are used to move it with respect to the body of the ASV. Full details concerning this leg can be found in [26,27,38]. This prototype formed the basis for a somewhat more compact design used for construction under Contract DAAE07-84-K-R001 of the six legs to be installed and tested on the ASV vehicle. Figure 2 shows one of the latter legs mounted on its servicing and assembly fixture. As suggested by this photograph, the final leg design is highly modular, thereby facilitating modification and maintenance.

it was determined that direct powering of individual leg joints, as occurs in industrial robots, is inappropriate for walking vehicles. Instead, for the latter, it is highly advantageous to utilize a lift system which opposes gravitational forces in order to maintain vehicle altitude above the terrain, and a drive system which provides the forces needed for forward motion [4,9]. It is necessary that these systems be mechanically decoupled in order to avoid actuator interactions which could result in serious wastage of energy [10].

One very attractive approach to achieving gravitational decoupling in walking machine leg design is to use some type of adjustable four-bar linkage mechanism in which continuous rotation of an input crank results in a basic cyclic motion of the leg with an approximately linear foot path, and with an actively-controlled adjustment of the length of some member of the linkage to vary the working height of a limb. The latter function is needed for ground clearance during swing phase and for terrain accommodation during support phase. Two experimental devices were constructed during the first year of this contract to investigate this approach. The first of these, the Monopod, was electrically powered, and used just one leg to propel and steer a three-wheeled cart [3,8,29]. This leg demonstrated a specific resistance of 0.3, the lowest value reported up to that time for any computer-controlled walking machine leg mechanism [3,13,60]. The second, the DUWE (Dynamic Unpowered Walking Experiment), was a computer-coordinated, six-legged, unpowered walking machine making use of a solenoid on each leg to adjust leg length for ground clearance during swing phase. Fore-aft leg motion coordination for the DUWE was accomplished by a pulley system which maintained proper leg phasing for a tripod gait [5]. Each set of three mechanically coordinated legs was latched in a raised position at the end of the return

2. MECHANICAL SYSTEM RESEARCH

The research described in this report was preceded by a one-year design study (DARPA Contract MDA903-81-C-9138) in which it was concluded that the current state of technology made it feasible to construct a six-legged computer-controlled walking machine with off-road mobility characteristics superior to those of any existing land vehicle. It was anticipated that this vehicle would be operated in a supervisory control mode in which a human driver would utilize displays and control devices similar to those found in advanced aircraft to determine a trajectory for the center of gravity of the vehicle, and to control its body attitude. A survey of available component technology lead to the further conclusions that such a vehicle could carry its own computer and prime mover, and would be capable of a top speed of about 8 mph., providing that a sufficiently efficient hydraulic actuation system could be developed. Finally, it was envisaged that the size and weight of this machine would be comparable to that of a light truck or a small helicopter.

This section of this report presents a summary of major research findings and the design rationale leading to the mechanical design of the ASV system under construction at the time of this writing. A following section provides similar information regarding electrical system design.

2.1 Leg Geometrical Design

Research carried out during the one-year design study which preceded this contract revealed the importance of "gravitational decoupling" in leg actuation. That is, based on experience with earlier walking vehicles [1,3],*

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*Numbers in square brackets refer to the list of publications presented in Appendix 1 of this report.

in a stationary mode with forced-air cooling at 70 hp continuous output. With respect to the electrical system, the Battelle guidance computer and the OSU control computer were successfully integrated to form a thirteen computer vehicle control system. The Battelle software for terrain data processing and foothold selection was shown to function correctly with the OSU software for vehicle leg and body control. This test was carried out by simulating both terrain and the ASV leg and body kinematics on the PDP-11/70 computer operating in real time while connected to the appropriate inputs and outputs of the vehicle breadboard computer. In another test, operator interaction was provided by connection of the cab-mounted controls and displays through the cockpit computer into the breadboard ASV computing system. This test also verified correct functioning of the multicomputer operating system which coordinates the actions of individual computers in this system.

Overall, by the end of the third and final contract year, enough experimental results had been obtained to provide a high degree of confidence that construction and initial testing of the ASV will be completed under Contract DAAE07-84-K-R001, within FY 85. Details of major project accomplishments supporting this view are provided in the following sections of this report. In subsequent contract years, it is expected that the ASV will serve as a versatile experimental basis for the design of a more advanced vehicle featuring greater agility, higher speed, and autonomous operation. Conceptual design of the latter machine, called the Agile Autonomous Vehicle (AAV), is the principal goal of Contract DAAE07-84-K-R001.

research efforts were to be concentrated on the completion of subsystems and on final vehicle assembly.

1.3 Third Year Research Summary

The first part of the third year (FY84) of research on this contract was devoted to testing of components delivered by vendors, to continuing detailed mechanical design, and to software development. In addition, the structure of a modular ASV cab was completed and delivered to the University of Wisconsin for installation of operator controls and displays. By the end of the fourth month of this contract year (January, 1984), both the vehicle flywheel system and the terrain scanning system with its associated guidance computer had been delivered to OSU. As a result of acceptance testing of these subsystems as well as of vendor-supplied components, several serious design and manufacturing errors were uncovered. These errors included out-of-tolerance mechanical components, potentially destructive flywheel vibrations at only fifty-percent of design top speed, and overheating and other significant problems with the terrain-scanner. Correction of these deficiences required considerable engineering effort and subsequent reworking of the affected components and subsystems. As a result, in consultation with DARPA, a revised program plan was developed under which anticipated completion of the ASV was delayed until early in calendar year 1985. A new contract (Contract No. DAAE07-84-K-R001) was negotiated to support this effort as well as subsequent testing and evaluation of the ASV.

By the end of the third and final year of Contract MDA903-82-K-0058, all known subsystem and component deficiences had been corrected, and final assembly of the ASV was in progress. Testing of the prototype leg confirmed earlier predictions of vehicle energy requirements. The engine was operated

Kawasaki air-cooled motorcycle engine as a prime mover [45]. Figure 6 shows this engine modified for stationary operation by the addition of a cooling shroud. A carburator water-injection system has also been installed and tested to provide a means for lowering combustion temperatures, if needed. This modified engine has operated on a test stand under full load with entirely satisfactory results.

Both the clutch and the gear system of the Kawasaki engine have been retained in the ASV vehicle to facilitate flywheel spin-up. The remainder of the mechanical power distribution system, consisting of gear-belt power take-offs to the three longitudinal lineshafts, to the alternators and controller pump, a second clutch between this main power take-off and the flywheel, a brake on the main drive shaft, and power take-offs by means of gear belts to each of the eighteen actuator hydraulic pumps, has been completely designed [59]. Installation of this system in the ASV is in progress at the time of this writing.

2.5 Optimal Limb Coordination

The above described work has resulted in a vehicle with an unsurpassed ability to actively alter its geometry and to control the interaction of its supporting elements with the terrain. As desirable as this result is, it leads to a very difficult theoretical problem; namely, how should this capability be used? That is, given the ability to actively adjust eighteen degrees of freedom, how should such motions be coordinated? Prior to this contract, this question had been studied extensively only for the case of straight-line motion over flat terrain [2,61]. Appendix 2 of this report [Reference 42] makes major theoretical contributions to this difficult problem in mechanics.

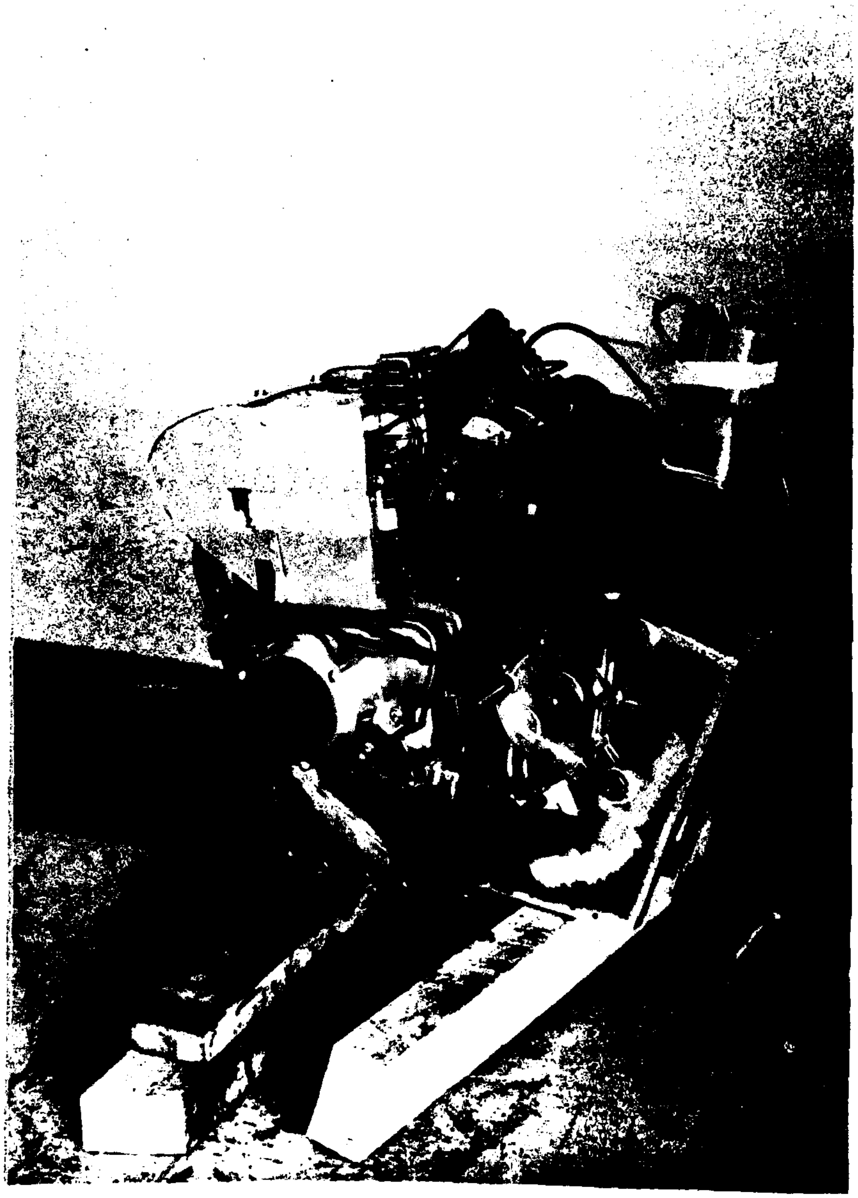

Figure 6. ASV prime mover showing cooling shroud added for stationary operation. Total weight is 200 lb.

While it is not possible to fully describe the results of Appendix 2 in this summary, the problems addressed and the general nature of the research findings are relatively easily understood. First of all, to appreciate the complexity of the problem, it is important to realize that for periodic gaits of hexapods there are 11! or 39,916,800 distinct choices for the sequence in which legs can be lifted from and placed upon the terrain [61]. Given this bewildering set of alternatives, it is essential that some systematic means be used to select a small number of gaits for further study. Two approaches have been used for this purpose in the past. One is to study insect locomotion, since natural selection should certainly be expected to produce gaits which are in some sense optimal [40]. The other is to define a mathematical index of performance which can then be optimized to suit various terrain conditions [39,61]. The latter approach is used in Appendix 2.

The first gait optimization problem considered in Appendix 2 relates to straight-line locomotion over level terrain at constant speed. While previous research on this problem showed that a set of six gaits, collectively called "wave gaits," produces optimal stability for such terrain, the optimization methods used assumed a pre-determined leg stroke [61]. In Appendix 2, this constraint is removed. The result is a significant improvement in stability over what was previously thought to be optimal [61]. This is a result of great practical significance which was immediately incorporated into prototype ASV control software [32,58].

The second problem treated in Appendix 2 is the development of new classes of gait to optimize criteria other than stability. Perhaps the most important part of this work relates to finding gaits which maximize the ability of the ASV to cross geometrical obstacles. The major finding in this area is that "in phase" gaits, in which the front pair of legs move (sequentially), then the middle pair, and then the rear pair, provide the best means for climbing steps and crossing ditches. This is in contrast to locomotion over level ground in which "out of phase" stepping (one-half cycle phase shift between any right-left pair of legs) produces optimal stability [61]. This was an unexpected result which also directly affected ASV control software. Even more surprising was the independent discovery that insects use essentially the same strategy when dealing with the same class of obstacles [40]. Prior to the work of [40], funded by our subcontract, only wave gaits had been observed in insect locomotion.

While much additional theoretical work is required to obtain a full understanding of the optimal use of the ASV legs in rough terrain locomotion, Appendix 2 and other work under this contract [12,14,18,24,25,33,55] has provided a firm foundation for such studies. Continuing research on this problem will be conducted under Contract DAAE07-84-K-R001.

3. ELECTRICAL SYSTEM RESEARCH

Prior to the beginning of the subject contract, considerable research concerning the problem of computer coordination of walking machine limb motion had been carried out in a number of research centers, principally in the United States, the Soviet Union, and Japan. This field of research originated with Prof. McGhee at the University of Southern California, in 1965, in a project which culminated in 1967 in the successful testing of a simple computer-controlled quadruped, the first such machine ever constructed [61]. Subsequently, after moving to Ohio State University in 1968, Prof. McGhee continued this work and, in 1977, demonstrated a second-generation walking machine, the OSU Hexapod [2,23,39,61]. This latter vehicle was the first walking machine to embody supervisory control in which a human operator is assigned the task of determining three body velocity components (forward, lateral, and turning velocities) while a control computer coordinates the motions of eighteen limb joints to produce the desired body motion. In this style of control, the computer is also responsible for maintaining the body parallel to the terrain and at a prescribed altitude above it, as well as for cycling limbs in such a way as to avoid encountering joint limits. Finally, in the control software realized before the start of research under this contract, in addition to realizing the above functions, for the case of locomotion over flat terrain, the control computer was also able to prevent limb collisions while at the same time maintaining vehicle static stability [2].

Viewed from the perspective of the above history, the ASV can be regarded as a third-generation computer-controlled walking machine representing a large advance over the OSU Hexapod in several respects. First of all, the OSU

Hexapod receives power from a 60 Hz electrical supply by means of a trailing umbilical cord which also provides a digital data link to its control computer (originally a PDP-11/45 system). Thus, this machine is suitable only for laboratory experiments. In contrast, since the ASV carries its own computer and prime mover, it amounts to a self-contained system capable of outdoor operation in natural terrain. A second major advance is that whereas, prior to the research of this contract, the OSU Hexapod had exhibited only locomotion over flat terrain, the ASV was from the beginning conceptualized as a system with a capability to overcome large obstacles. Finally, a major goal of research under this contract was to provide a test bed suitable for studies of autonomous behavior. As a consequence, the ASV was designed to carry a human operator, some of whose functions are paralleled by an optical terrain scanner and an associated guidance computer. With this feature, it is possible to investigate a spectrum of levels of operator intervention in vehicle control ranging from supervisory control, as in the OSU Hexapod, to full autonomy in which the operator is removed from the cab [17,35,36,61].

In this section of this report, a summary of major research findings which have provided the basis for design of both the ASV electrical and electronic systems and the associated computer software is presented. Further details can be found in the research publications listed in Appendix 1 and referenced in the following text.

3.1 Experiments with the OSU Hexapod

At the start of research under this contract, no computer-controlled walking machine had demonstrated rough-terrain locomotion under supervisory control. Since this was to be a major feature of the ASV, during the first year of this research a high priority was given to modifying the hardware and software of the OSU Hexapod to provide it with this capability. With regard to hardware, vector force sensors were added to all legs and a vertical gyroscope and pendulum sensors were installed in the body. This work is reported in detail in [7,17]. In addition, the PDP-11/45 computer was replaced by a more powerful PDP-11/70 computer. After these hardware changes, software was written which enabled the OSU Hexapod to operate in a supervisory control mode over laboratory rough terrain [6,7,12,23]. Figure 7 illustrates typical results obtained during evaluation of this software in the first year of this contract [9,17].

While inertial and force sensing provide adequate information for automatic regulation of body attitude and altitude, such sensing is not able to prevent the limbs of a walking machine from occasionally colliding with the supporting substrate during rough-terrain locomotion. This means that a walking vehicle limited to these sensory modalities must be operated only at speeds low enough to permit such collisions to occur without incurring damage to the limbs or even, possibly, upset of the entire vehicle. To overcome this limitation, some advance information is needed to provide an estimate of terrain contours. In terrestrial animals, such "preview" information is obtained either from vision or by tactile probing of the terrain [40,61]. For the ASV, due to the generally poor performance of available vision systems using television images, it was decided at an early stage that a scanning optical range-finder should be used so as to completely bypass the problem of reflectance image processing. However, since no such scanner was available at the start of this research, during the second contract year, the OSU Hexapod was further modified to provide it with an elementary type of triangulation ranging system. This ranging system, described in [18,21,24,39,50], was human

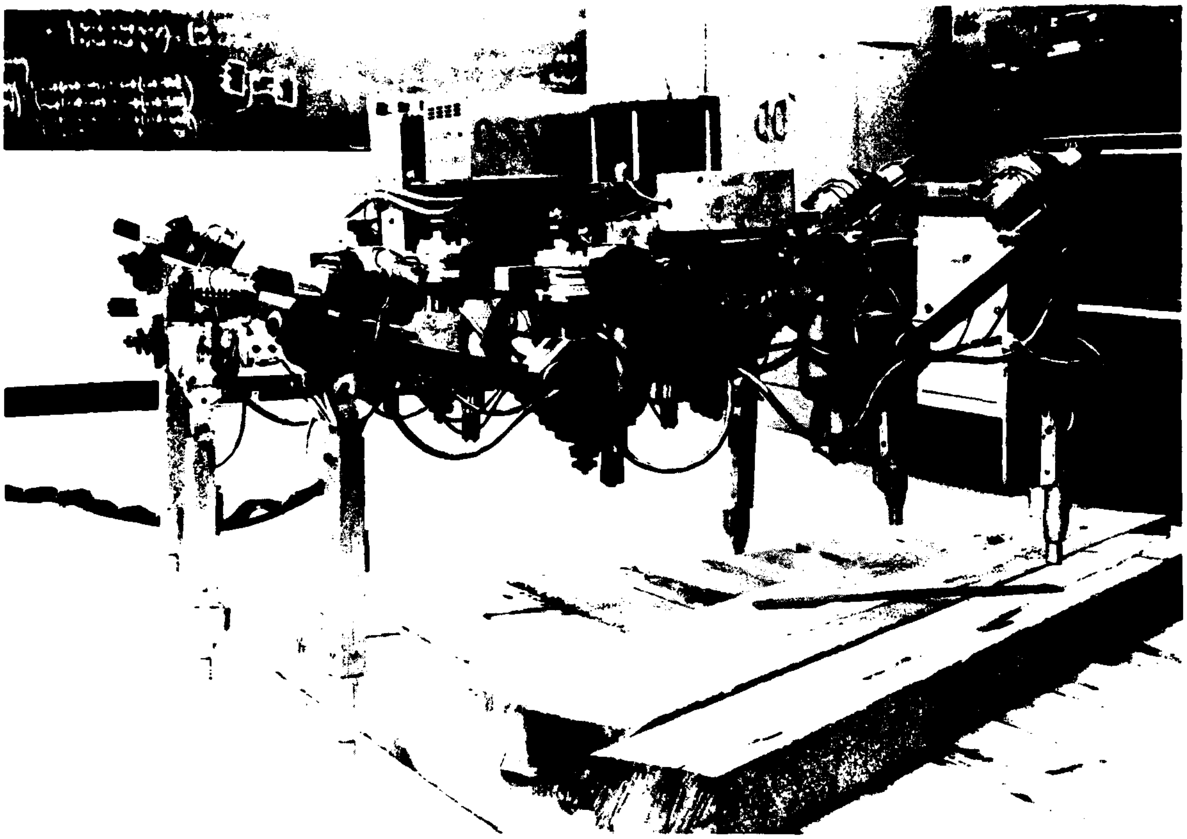

Figure 7. OSU Hexapod Vehicle showing ability to maintain body level while traversing rough ground. Attitude control achieved using force feedback from feet and vertical gyro for body attitude sensing.

interactive in the sense that an operator designated potential footholds on the laboratory terrain shown in Fig. 7 by means of a hand-held Helium-Neon laser. The OSU Hexapod vision system then used two CID television cameras to triangulate on these points to determine their location in its body coordinates and accepted or rejected them depending on their suitability [24,39,50]. These cameras can be seen on the modified OSU Hexapod structure shown in Fig. 8. While not intended as a practical means for walking machine control, experiments with this simple ranging system constituted the first demonstration of integration of range information into the foothold selection software of a walking machine, and provided a basis for the subsequent evolution of software for the ASV in which range data is obtained from the ERIM scanner [35,36].

In addition to using optical terrain preview information, the OSU Hexapod was further modified to provide ultrasonic proximity sensing in the vertical direction for each leg [22,35]. This approach worked well on the terrain of Fig. 7, but was found to be unreliable in soil-bin tests due to occasional destructive interference of the ultrasonic energy scattered from different points of the terrain surface. Nevertheless, the knowledge gained from this experiment was basic to a subsequent redesign of the proximity sensing system in which multi-frequency Polaroid transducers were utilized. The latter system was successfully tested on the prototype ASV leg described in the preceding section of this report [52].

In addition to its use in sensor evaluation and integration, the OSU Hexapod provided a valuable basis for studying control mode alternatives and man-machine interaction for the ASV. During the first contract year, software was developed in which a commercial voice response unit was used to inform an

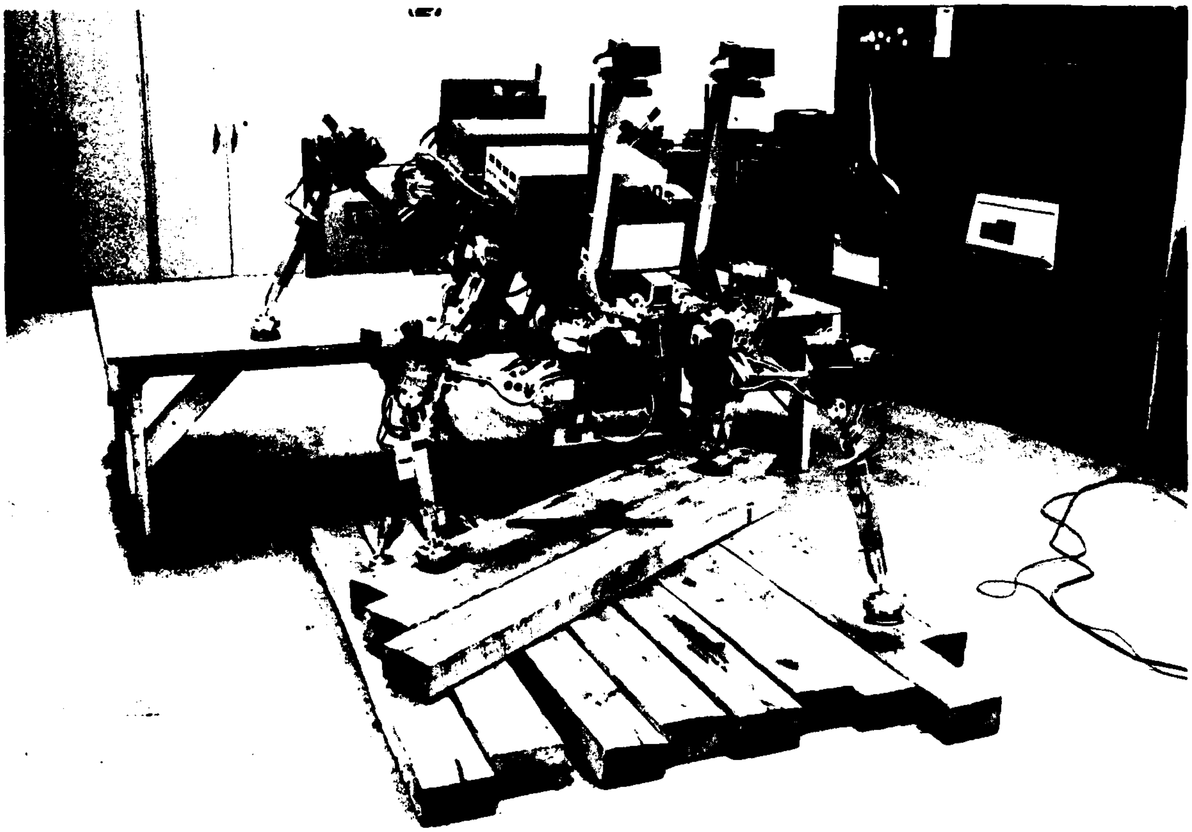

Figure 8. Precision footing control of OSU Hexapod showing ability to overcome large obstacles.

operator of computer intervention in the supervisory level of control to prevent limb collisions or loss of vehicle static stability [6]. While the value of such verbal communication relative to visual communication by means of a CRT display has yet to be determined, an improved version of the safety algorithms presented in [6] has been incorporated into the ASV operational software.

During the second contract year, human-interactive software was developed which allowed the operator of the OSU Hexapod to dynamically assign the three axes of his joystick to any one of eight velocity control functions: body translation, body rotation, or Cartesian coordinate foot motion for any one of the six feet. In every case, the other vehicle degrees of freedom are automatically regulated by the computer [35]. Using this control scheme, as shown in Fig. 8, the OSU Hexapod was able to climb over a table with dimensions comparable to its own body. This software was subsequently adapted to control of the ASV in "precision footing" mode [17,35,36]. Finally, during the third year of this contract, this control mode was further refined to allow the legs of the OSU Hexapod to be maneuvered as two independent sets of tripods while at the same time providing for automatic movement of the vehicle center of gravity to an optimally stable point [55]. While this approach worked well for the OSU Hexapod, its utility for control of the ASV is still under study.

3.2 Operational Modes for the ASV

In [17,35,36], a total of six ASV operational modes are defined. The first of these, called <u>utility</u> mode, is used for system checkout, maintenance, and modification, and assumes that the ASV is resting on its belly skids or is otherwise secured. The second is the previously referenced precision-footing mode in which the operator may move either the body, or any selected leg, but not both. The third mode, called close-maneuvering, relies upon operator control of omnidirectional body motion (six degrees of freedom), but cycles limbs automatically. This control mode is used only at low speeds and does not make use of the ERIM terrain scanner. A variant of this mode provides automatic regulation of body pitch and roll, reducing the operator's task to a four degree-of-freedom problem [32,58]. In either form, close-maneuvering provides the kind of arbitrary body motion capability previously found only in helicopters. Because it does not use terrain scanner data and limb collisions with the terrain are therefore possible, body velocities in close-maneuvering mode will be limited to about 1 mph.

The most automatic ASV control mode is called terrain-following. In this mode, the optical terrain scanner of the ASV produces a local map of terrain elevation in Cartesian coordinates. The on-board guidance computer then classifies the resulting terrain cells as acceptable or unacceptable for use as footholds. Subsequently, using operator designated body velocities, a sequence of acceptable footholds is selected and used by the ASV [33]. During this process, body altitude above the terrain as well as body pitch and roll attitude are automatically regulated. Since the ERIM terrain scanner is rigidly mounted to the ASV body, it is able to see only terrain cells encompassed by its azimuth scan of ±40 degrees, and within its maximum range capability of 32 ft. For these reasons, as well as for computational speed limitations, ASV locomotion in terrain-following mode is restricted to a top speed of 2 to 3 mph. Moreover, to ensure that an adequate map is available for foothold selection, the minimum turning radius allowed in this mode is of the order of two body lengths.

For higher speed locomotion over relatively smooth terrain, two additional ASV modes have been defined. The first of these, called cruise, is a mode which optimizes fuel economy. To achieve this goal, a fixed tripod gait using a maximum stride length is utilized. The use of the scanner is limited in this mode to control of body attitude and altitude above the terrain. To avoid leg interference problems, the body crab angle is restricted to approximately ±10 degrees and the minimum turning radius is increased to 3 or 4 body lengths. To avoid foot collisions with the terrain, the leg return height is set at a value high enough to clear the maximum size obstacle anticipated by the operator. Generally speaking, in this style of control, the behavior of the ASV will be analogous to that of a fixed-wing aircraft.

If fuel economy is sacrificed and stability is somewhat compromised, the ASV should be capable of locomotion at speeds up to 8 mph. The dash mode is designed to provide this capability. In dash mode, there may be short periods of time in which the ASV is supported by as few as two legs. It is anticipated that such a gait, analogous to a quadruped trot, would produce a rather rough ride and would result in poor fuel economy. Its practical use would therefore probably be restricted to emergency situations.

While it is certainly possible to imagine many other operational modes for the ASV, and some of these have been investigated using the OSU Hexapod as a test bed [22,55], the selection of sensors, cockpit displays, and operator's controls for the ASV has been determined primarily by the characteristics of the modes described above. The following text provides a description of these items.

3.3 Sensors

In order to support the operational modes described above, the ASV is furnished with an optical terrain scanner capable of providing a range map at a 2 Hz rate. In generating this map, the scanner sweeps a laser beam over the terrain with an azimuth angle coverage of approximately ±40 degrees from the ASV longitudinal axis, and an elevation angle coverage of -15 degrees from the horizon to -75 degrees. With the vehicle geometry shown in Fig. 1, this provides a nominal maximum range of about 32 ft. During each elevation scan, the azimuth scanner sweeps out 128 lines in evenly-spaced elevation angle increments. For each of these lines, 128 range values are returned at evenly-spaced azimuth angle increments. Each range value is at a resolution of 8-bits, modulo 32 ft. Thus, each frame of data from the terrain scanner amounts to a 128 x 128 array of 8-bit range values. Figure 9 shows the overall external appearance of the terrain scanner. Detailed specifications for this system are available from its manufacturer, the Environmental Research Institute of Michigan (ERIM).

Within the ASV computer, scanner data is converted to rectangular coordinates before storage in the form of an elevation map. In addition to the raw scanner data, the ASV also uses information from an inertial reference system to accomplish this function. This is necessary because the scanner deflection angles are measured in body coordinates whereas the elevation map is maintained in Earth coordinates. The inertial reference system is of the strapped-down variety, and makes use of three linear accelerometers, three vibratory rotational-rate sensors, and a two-axis vertical gyro as its primary sensing means. A redundant sensor in the form of an additional two-axis vertical gyro will also be included in the ASV for use by the safety system in detecting primary sensor failure.

means, one of the 28 volt sources can fail, and the other will still provide more than adequate power to maintain the batteries at full charge. The 24 volt supply is used to power all electrical systems except for the computer and some sensor systems.

As can be seen in Fig. 13, the computer is furnished with two identical power supplies. Each of these supplies operates from one of the two independent 290 volt DC alternator outputs. The various outputs of the computer power supplies are connected pairwise in parallel through current-sharing regulators with an ability to instantaneously and automatically switch the full electrical load to one supply if the other should fail.

Since it will often be desirable to operate the ASV computer with the engine off, a separate external alternator system has been designed. This auxiliary power source, shown in Fig. 15, uses an alternator identical to the on-board system. Because of its capacity, this alternator can replace the function of both vehicle alternators during static operation of the ASV electrical systems. This system will eventually be installed in a service and instrumentation van to be used to support ASV operation and evaluation during field testing.

3.7 Software

The control software associated with the ASV on-board computer represents a major advance in off-road vehicle technology which transcends its immediate application. Specifically, the software for vehicle control is organized into a three-layer hierarchy which explicitly recognizes a logical level, a kinematic level, and a servo level. As shown in Fig. 16, due to the multiprocessor nature of the ASV computer, this organization is also reflected (safety-valve firing) shutdown. This characteristic of the ASV system is a result of deliberate choices dictated by size, weight, and cost considerations. That is, the ASV is a proof-of-concept vehicle and not an operational prototype. This being the case, reliability was compromised in order to improve other aspects of system performance. This is, of course, undesirable in the long run, and research has been initiated into effective ways of obtaining fault tolerance in an improved on-board computer [11,34,56]. However, while some hardware experiments are now underway, it is currently expected that time and cost considerations will prevent the inclusion of any significant fault tolerant capability in the ASV computer system before the end of the current contract (April, 1987). Rather, experience gained from ASV testing, and from laboratory experiments with fault-tolerant computer architectures, will be used to provide a recommended configuration for the fourth-generation AAV walking machine being designed under the current contract.

3.6 Electrical Power System

The electrical power needs of the ASV are currently estimated to total not more than 2 KW, consisting of 1 KW for the computer, and 1 KW for all other systems. Since loss of electrical power is potentially catastropic for the ASV, its on-board power sources are fully duplexed, with either system being capable of handling the full vehicle load. The primary source of electrical power for either of these systems is provided by one of two independent alternators rated at 5 KW each. Each of these alternators is driven by a gear belt from the mechanical power transmission system of the ASV and produces a 28 volt DC and 290 volt DC output. The 28 volt DC lines are connected in parallel through diodes to a 24 volt battery system. By this systems. Each such box contains signal conditioning amplifiers for transmission of sensor data to the computer, as well as servo amplifers which control the swash-plate angles of the three variable-displacement pumps associated with the actuators of each leg. As can be seen from Fig. 12, the set-point for each of these servo amplifiers is provided by an analog signal from the associated leg control computer.

Tests to date indicate that the ASV computer currently possesses adequate capability for all but two of its tasks: terrain scanner data processing and optimal distribution of desired body forces to each of the eighteen joint actuators. The first of these problems is presently solved by reducing the resolution of the terrain elevation map used by the guidance computer to use only one out of sixteen range pixels provided by the scanner. This effectively decreases the scanner angular resolution by a factor of four in both scan directions. The second problem is dealt with by using a sub-optimal force allocation algorithm based on psuedo-inverse calculations [7,23]. It is felt that both of these problems can be solved through the use of relatively simple special-purpose computer systems compatible with the Intel 86/30 computer boards. For the present, however, this has not been done, and some degradation of ASV performance in initial testing can therefore be expected. On the other hand, both of these problems are now receiving considerable attention, and it is expected that they will be resolved by a computer upgrade currently scheduled for the latter part of FY 86.

Another shortcoming of the ASV on-board computer is that it possesses no fault tolerance. Thus, while many types of failure can be detected by the safety computer, few can be corrected and, generally speaking, the only recourse available in case of subsystem failure is a controlled or emergency

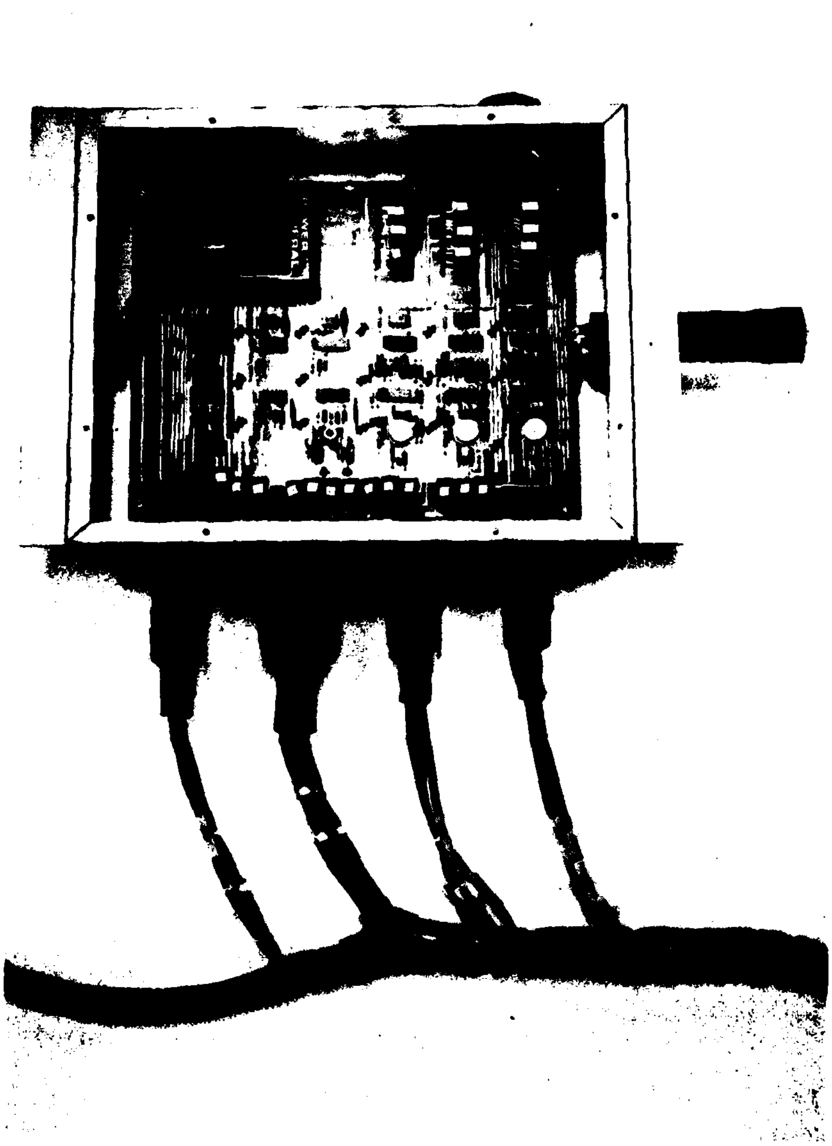

Figure 14. ASV leg electronics box and associated cables. Each such box interfaces one leg to on-board computer.

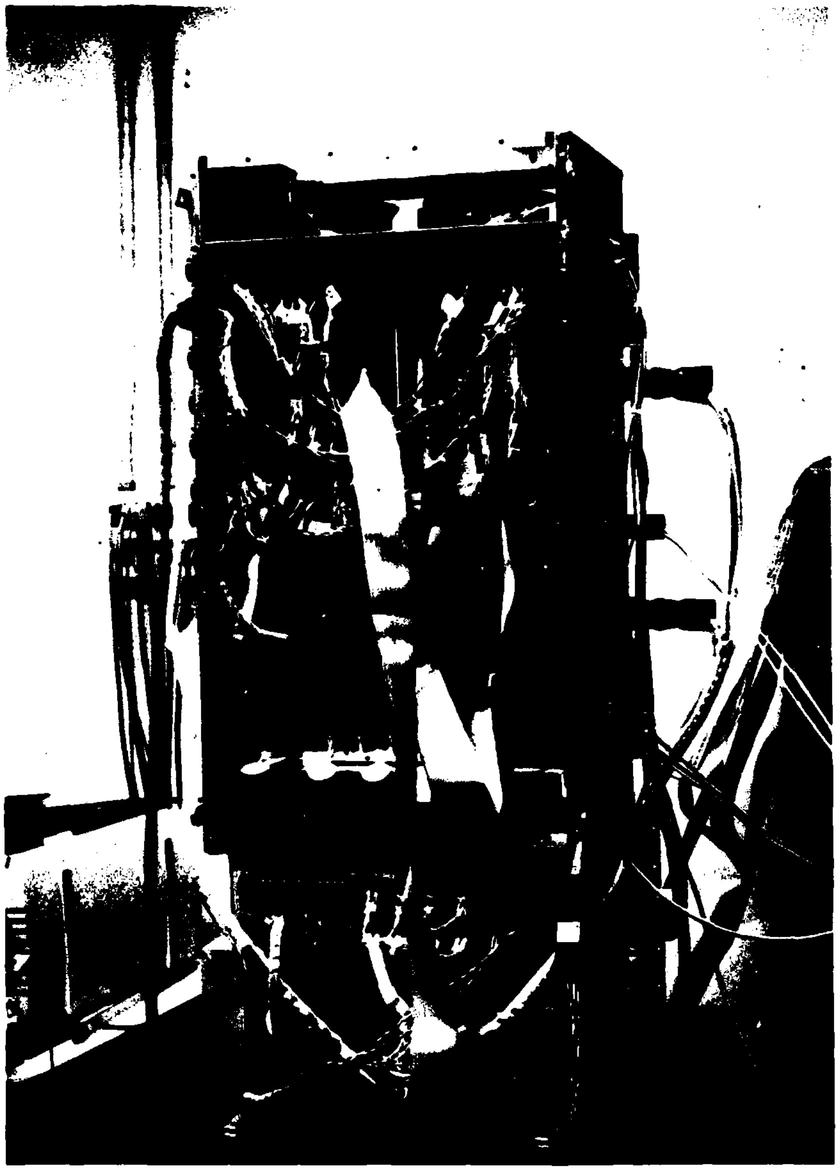

Figure 13. ASV on-board computer under test in laboratory. Power supplies are under computer. Computer box will be mounted horizontally in ASV in forward bay behind cockpit.

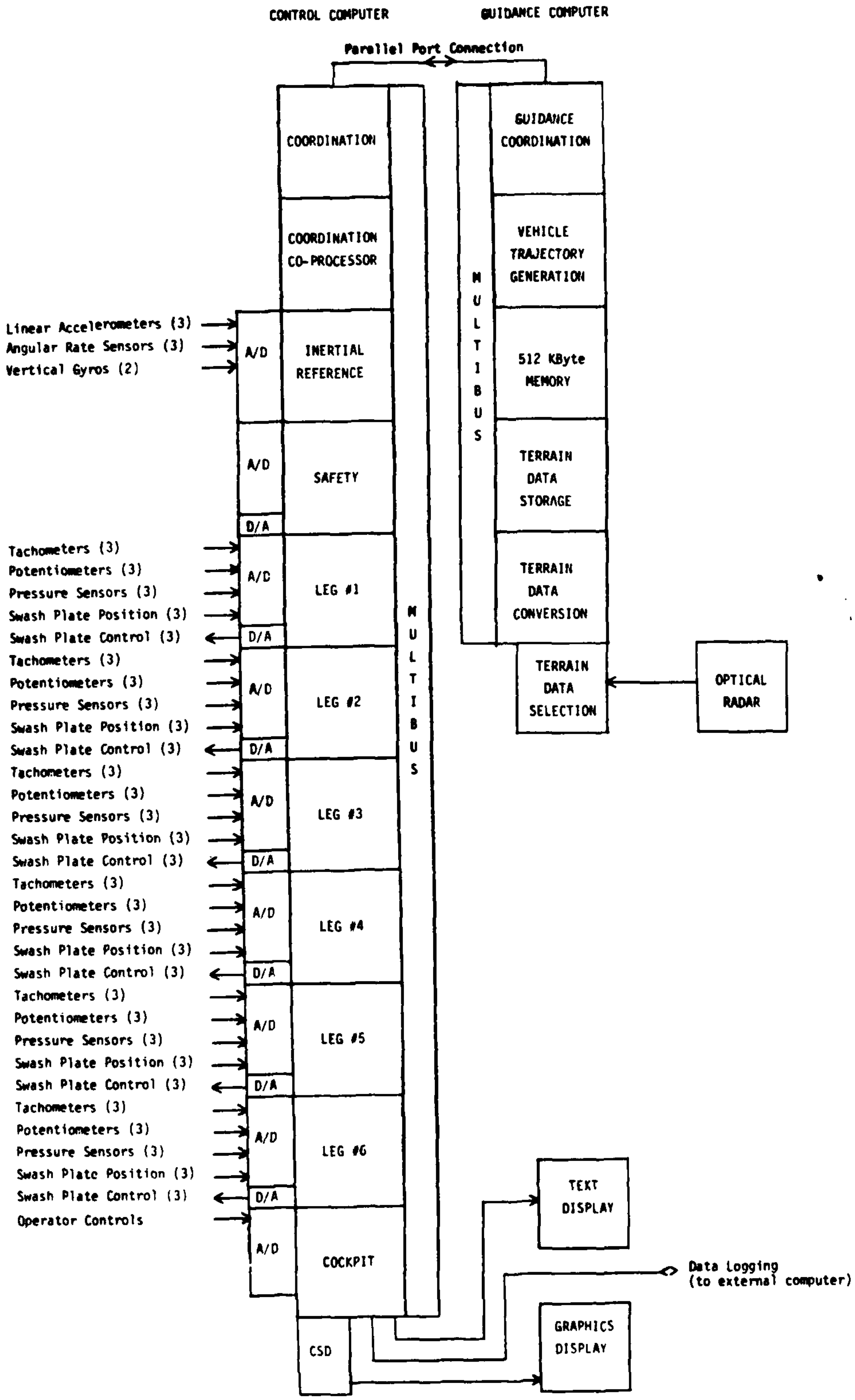

Figure 12. Block diagram of ASV on-board computer showing analog data channels and Multibus connections.

for the ASV based on 86/30 boards was designed and constructed by Battelle Columbus Laboratories under a separate DARPA contract. These two systems were integrated during the third year of this contract resulting finally in the system illustrated by Fig. 12. Figure 13 shows the physical components corresponding to this hardware organization.

As can be seen from Fig. 12, a total of fifteen single-board computers make up the current configuration of the ASV on-board computing system. Two of these boards, the coordination co-processor and the inertial reference computer, were added under Contract DAAE07-84-K-R001 to provide assistance to the single coordination computer included in the earlier thirteen board ASV computing system [35,36]. Each of the boards in the ASV computer contains an 8086 microprocessor, an associated 8087 arithmetic co-processor, 128K bytes of RAM, an optional A to D and D to A system, and various I/O channels. All computers in the system are connected via serial ports to a 9600 baud multiplexer system for downloading of programs and parameters from an Intel Microprocessor Development System. The connection of these boards to each other via the two Multibus systems as well as the assignment of analog input and output lines is also shown in Fig. 12. This figure in addition shows digital data paths to the terrain scanner, to cockpit displays, and to an external computer system, to be used for diagnostics and analysis of operational data.

The computer box and power supplies shown in Fig. 13 will be installed in the top half of the ASV frame directly behind the operator's compartment. The total weight of this system is approximately 180 lb. The computer will be connected by means of analog signal cables to leg electronics boxes mounted on the frame near to each leg of the ASV. Figure 14 shows one of these

In addition to the devices described above, the ASV prime mover and mechanical power transmission system will have cab-mounted controls. These will include at least an ignition switch, a mechanical gearshift, controls for a clutch and a main drive-shaft brake, and an engine throttle. Although the engine and transmission will be under automatic control in normal operation, manual over-rides will be retained for use in abnormal circumstances. As experience is gained with ASV operation, other means for interaction with the prime mover system may be introduced. One likely candidate for such a control is a manual device for arming and firing the explosively actuated safety valves associated with each of the eighteen leg actuators.

3.5 On-Board Computer System

Experience with the OSU Hexapod permitted a reasonably accurate estimate of ASV computing needs at an early stage of this research program. By the end of the first year, it was anticipated that real-time control of this vehicle would require computational power equivalent to that of one or two VAX 11/780 computers. Since this solution is manifestly impossible for a self-contained system in the ASV size and weight range, it was concluded that only a multiprocessor system based on high-speed microcomputers could provide the needed capability with an acceptable weight and volume. After some preliminary experiments [11,15,34,46], it was decided that the Intel 86/30 single-board computer provided the best commercially available building block for the ASV computing system. Accordingly, a major software analysis study was undertaken to determine an effective partitioning for multiprocessor implementation of the previous uniprocessor software system developed in connection with the OSU Hexapod [7,23]. At the same time, a guidance computer

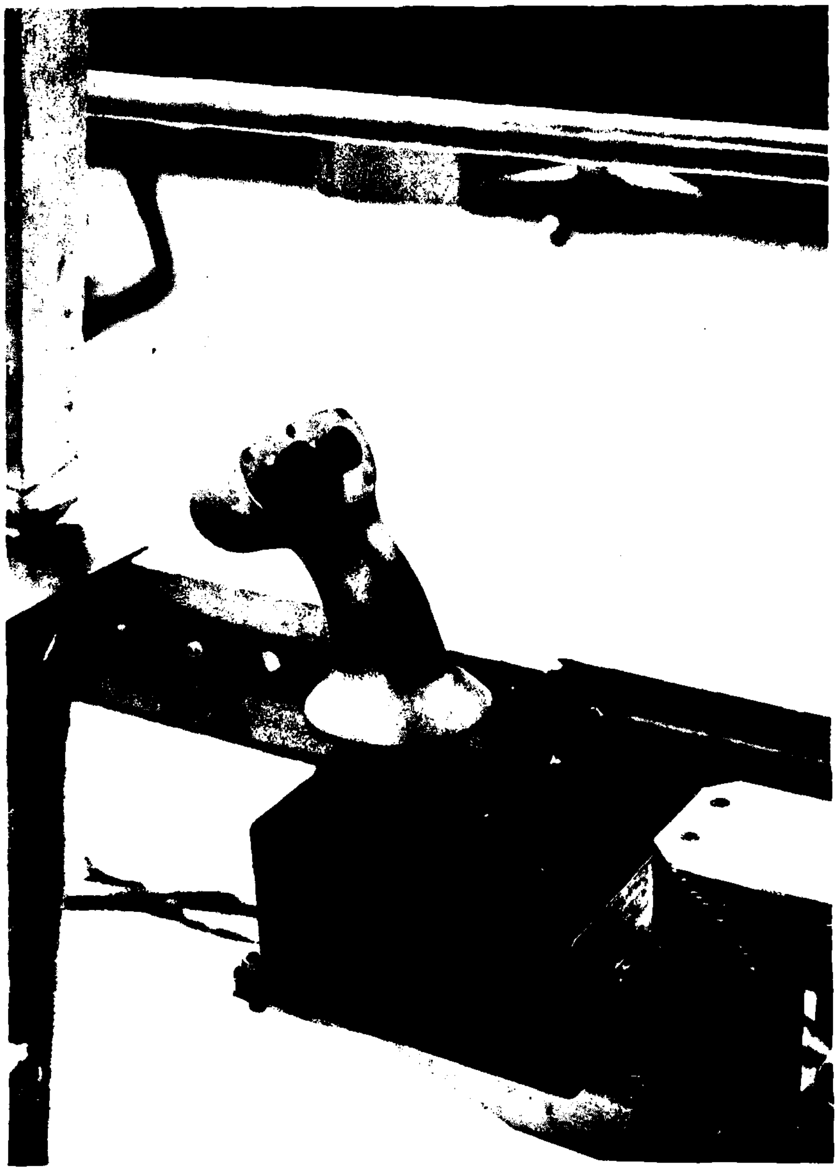

Figure 11. Three axis hand-controller showing thumb-operated miniature force-sensing joysticks. Left joystick button provides two additional degrees of freedom, right provides one.

by a function key pad, or other input system, which will allow easier mode selection by the operator and will be suitable for outdoor operation.

Continuous inputs to the control computer are provided by the six-axis control stick shown in Fig. 11. Three degrees of freedom for this controller are associated with fore-aft deflection, lateral deflection, and twist. The other three degrees are furnished by two miniature force-sensing joysticks mounted near the top of the handgrip. These two control sticks, evident in Fig. 11, are thumb-operated. The right joystick has one up-down axis and the left has both an up-down and a left-right axis. The basic three-axis joystick mechanism was designed and constructed by the University of Wisconsin, and later modified by OSU to include the thumb-operated devices. The final controller configuration is the result of a comparative evaluation at the University of Wisconsin which made use of a full-size mockup of the ASV cab together with a projection television system to represent terrain motion as seen from the vehicle. In addition to the selected joystick concept, this study investigated a controller in which fore-aft joystick motion was replaced by a sliding axis, and another in which an aircraft-style yoke handgrip was used [20].

Until now, in the development of ASV control software, the three major axes of the selected hand-controller have been used only for control of body velocity in the forward, lateral, and yaw rotational directions. The thumb-operated joysticks are used either for the other three degrees of body motion (roll, pitch, and altitude), or for leg control, depending on operator mode selection. While this assignment of control-axis functions seems natural and effective in the laboratory, a final decision on this question cannot be made until after extensive field testing of the ASV, currently scheduled for FY 86.

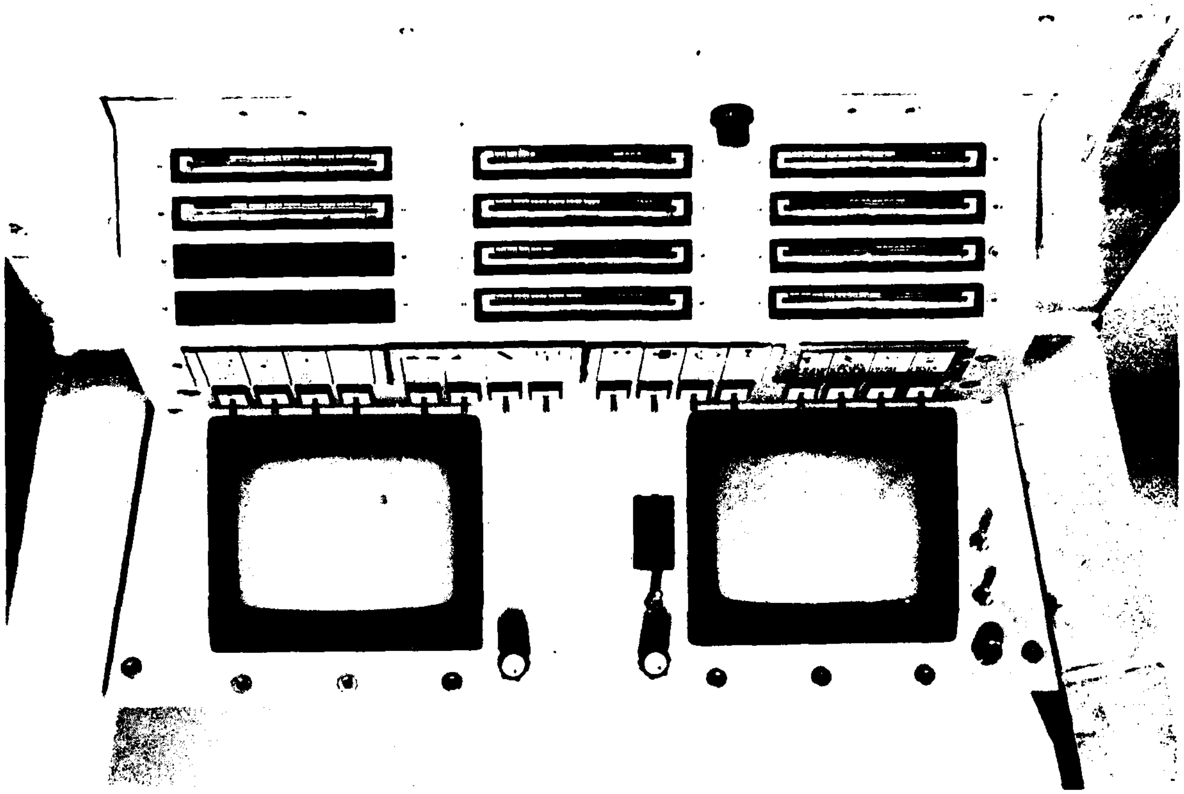

Figure 10. Cockpit displays. Left CRT is for graphics, right is for alphanumerics. LED gauges show primary system status variables.

3.4 Displays and Operator's Controls

As described above, the operator of the ASV interacts with the machine in two different ways. One form of interaction is at the level of discrete decision-making based on the system status. Examples of such decisions include execution of startup and shutdown sequences, operational mode selection, leg sequencing, etc. To assist him in such tasks, the operator is provided with two types of displays as shown in Fig. 10. As can be seen, at present the ASV provides hard-wired LED displays of ten primary system variables of the type described in the preceding discussion of sensors. Two unused slots in this display panel have also been included for future expansion of this system. In addition to the LED gauges, also shown in Fig. 10 are two raster-scan CRT displays. One of these is used for presentation of alphanumeric information, while the other provides a graphical display capability. The latter is especially helpful to the operator for the second type of man-machine interaction, continuous control of body and leg motion. Since this aspect of operator control involves the human directly in the vehicle dynamical behavior, it must be computer-driven. As described in a subsequent section of this report, one Intel 86/30 single-board computer is devoted to this function.

Analogous to the organization of the vehicle displays, the ASV operator controls must provide a capability for both discrete and continuous inputs from the operator to the vehicle computer, as well as to certain other subsystems. Discrete inputs include a row of sixteen function switches, located below the CRT displays and also visible in Fig. 10, as well as an alphanumeric keyboard. A temporary keyboard installation in the vehicle cock can be seen in Fig. 4. After initial indoor testing, this keyboard will be replaced

The above items permit the ASV to obtain a local description of terrain and to determine the position and orientation of its body relative to the resulting terrain data-base. However, for control of motion, additional sensing is needed. Specifically, each leg of the ASV is provided with position, rate, and force sensing at each of its actuators [52,53]. Moreover, on an experimental basis, the prototype leg has successfully demonstrated autonomous control of ground clearance during the swing phase of leg motion using foot-mounted ultrasonic proximity measurements. However, since this system is not sufficiently rugged for outdoor use, it will not be installed on the ASV until a satisfactory redesign for this purpose has been accomplished [52].

In addition to the above sensors needed for computer coordination of limb motion, a number of other sensors relating to vehicle operational status are provided in the ASV. These sensors include those normally found in automotive vehicles such as fuel level, water temperature, oil pressure, etc. However, due to the unusual nature of the ASV, other primary system status sensors are needed. These include flywheel speed, computer power-supply voltage, hydraulic oil temperatures, etc. Sensors for these status variables will also be installed. Provision for expansion of the number of sensor inputs to the computer system, and for display of additional status information to the operator, will be included in the system.

Generally speaking, primary system sensors are hard-wired to LED gauges so as to permit appropriate operator intervention in the determination of the vehicle status without the assistance of the on-board computer. Other sensory information is generally processed and presented in graphical or alphanumeric form on CRT displays. The next section of this report further discusses these matters.

Figure 9. Optical terrain scanning system developed by ERIM. Width = 26 inches, height = 12.5 inches, total weight = 75 lb.

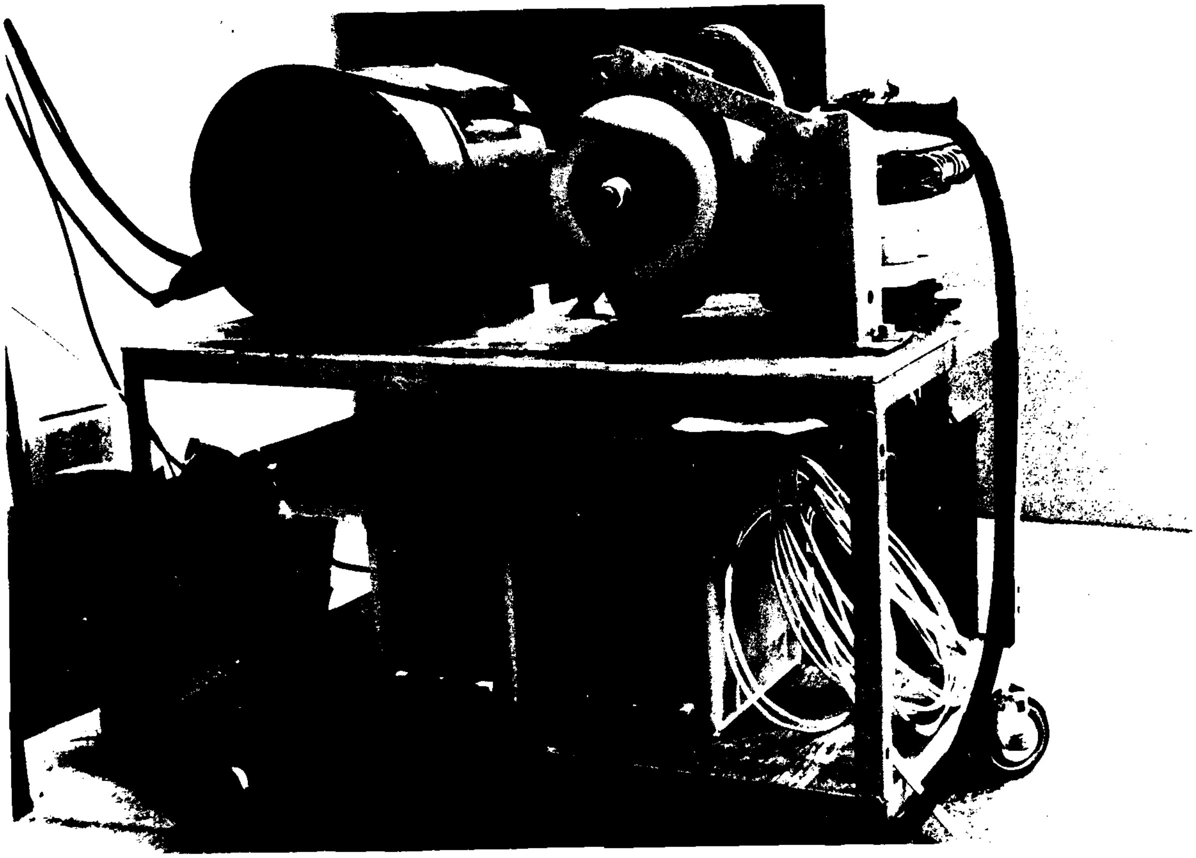

Figure 15. Auxiliary alternator to be used as external power source while operating ASV electronic systems with engine off.

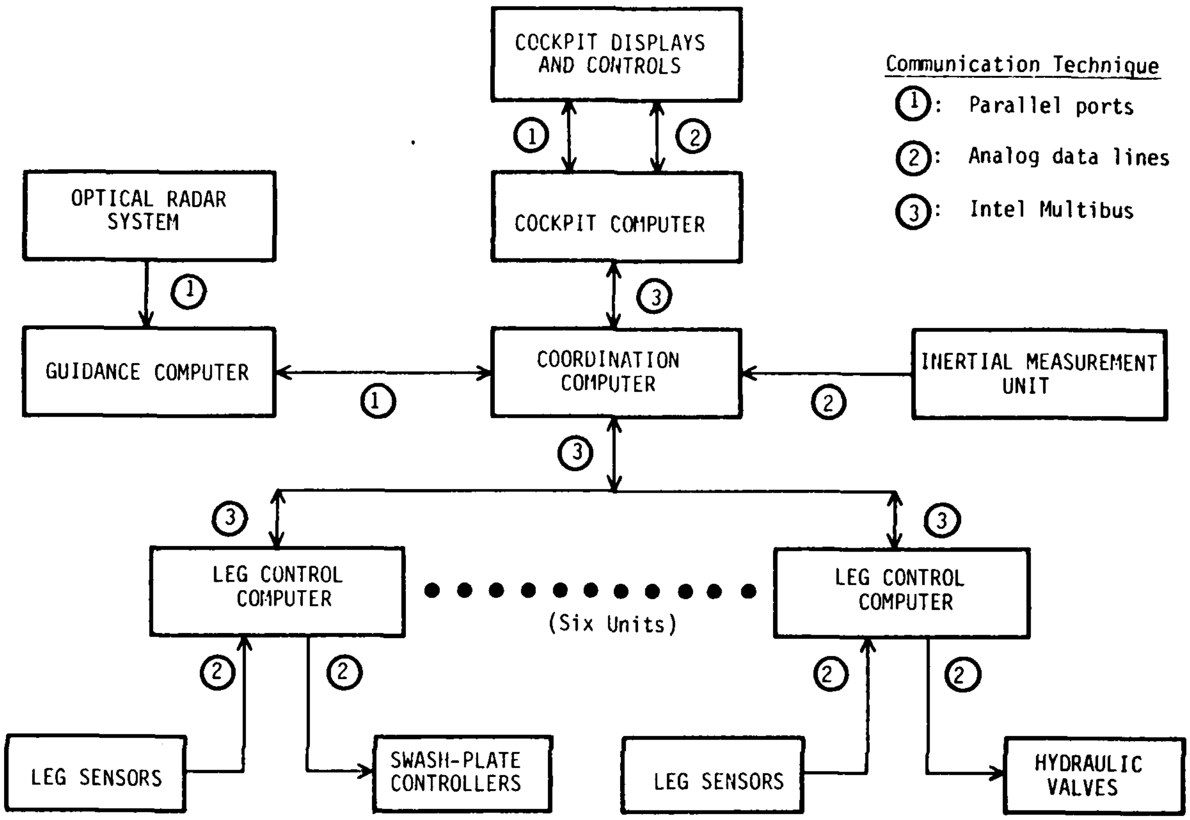

Figure 16. Block diagram of ASV computer system showing three-layer hierarchical organization of hardware and software.

in the hardware components of this system. This structure allows separate design and optimization of each of level of control, and provides a basis for the evolutionary development of terrain adaptability and autonomy beyond what has been possible with any previous land vehicle. This entire application software system is currently being implemented in PASCAL [35,36].

As can be seen from Fig. 16, and as was implicit in the earlier discussion of operational modes and computer hardware, the lowest level of ASV control is at the leg servo level. As shown on Fig. 12, each leg computer receives position, rate, and force (differential pressure) measurements from each of its actuators in analog form. In addition, via the Multibus, each such computer receives desired values for foot velocity and ground reaction forces, both expressed in body coordinates. Explicit leg state commands (swing or stance) are also transmitted by this means from the coordination level. Using its internal model of the leg and actuator system kinematics and dynamics, each leg control computer combines its digital and analog inputs to determine a desired setting for the swash-plate angle of its associated variable displacement pumps. This value is then transmitted in analog form to the analog swash-plate controllers described in preceding sections of this report. Full details concerning this system can be found in [19,28,44,49,52,53]. At the time of this writing, fully satisfactory operation of this level of control has been demonstrated using the prototype leg described in Appendix 2.

While development of a high performance leg control system was a difficult and central task in this research project, from a conceptual point of view, this problem is fairly easily understood. This is not the case with the kinematic or coordination level. As can be seen from Fig. 16, the coordination computer receives information from the guidance computer, the cockpit computer, and the inertial measurement unit. Given these generally conflicting inputs, it must determine a foot velocity and a vector ground reaction force for each leg. In so doing, it must maintain vehicle stability, avoid limb collisions and actuator limits, assure that all foot forces are directed within the friction cone of each foot (or possess a strategy for dealing with foot slippage), and regulate the body attitude and velocity to set points determined jointly by the guidance computer and the human operator. In addition, the coordination level of control is responsible for firing the explosively-actuated safety valves in the event of serious hardware or software failure. While the details of this system are still being worked out, with the exception of safety functions, software for the precision-footing control mode has been completed and tested in the breadboard ASV computer. Figure 17 is a photograph of the graphical display presented by the cockpit computer to assist the operator in this mode.

With respect to modes other than precision footing, many of the basic algorithms for the coordination level of control have been validated by simulation means or by experiments with the OSU Hexapod [2,12,14,23,25,32,33,39,42,55]. These experiments together with results obtained from implementation of precision footing control on the ASV on-board computer have resulted in a good understanding of computational needs at the coordination level. This understanding is reflected in Fig. 12, which shows a total of four Intel 86/30 boards dedicated to this function. These computers, whose names suggest their functions, are designated as: coordination, coordination co-processor, inertial reference, and safety. As mentioned previously, the coordination co-processor and inertial reference computers represent a recent

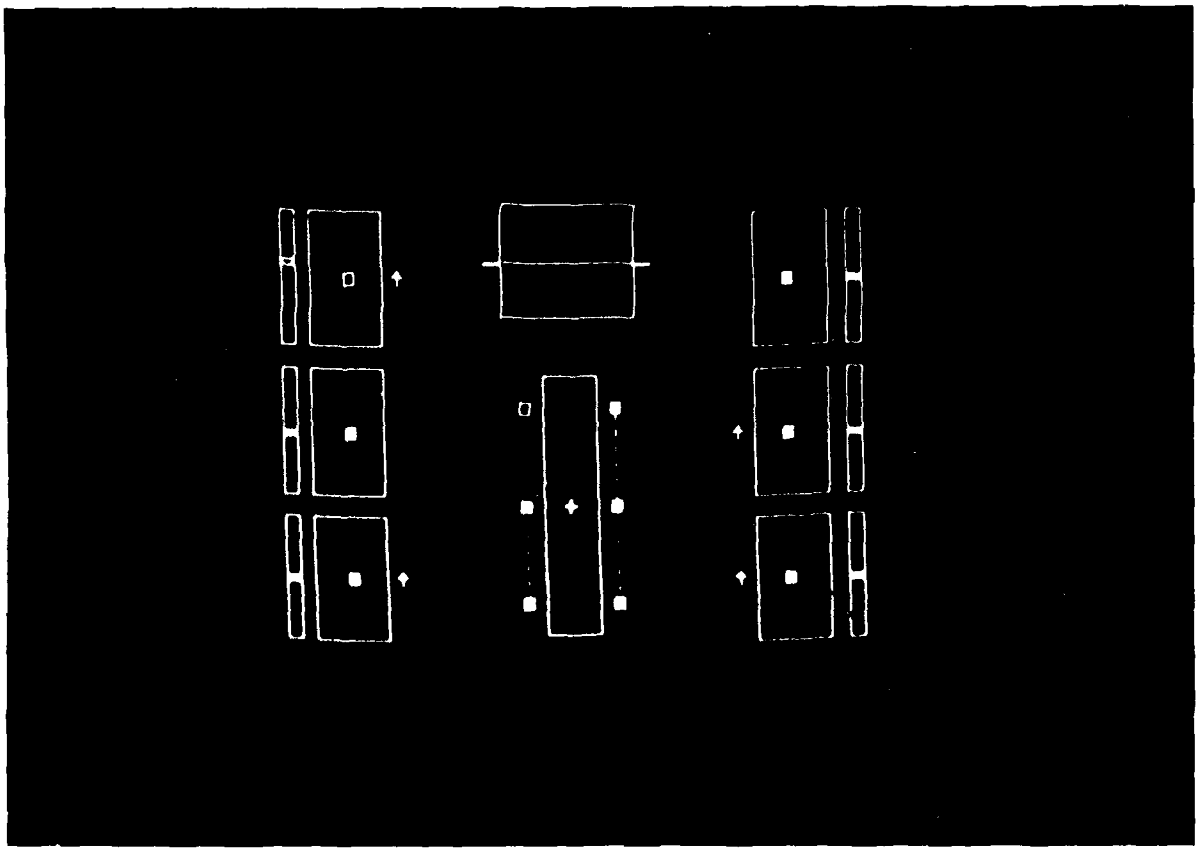

Figure 17. Precision footing graphical display on operator's CRT. Vertical bars show position of piston in lift actuator. Boxes show fore-aft and left-right kinematic limits of feet. Small solid rectangles show supporting foot positions. Open boxes indicate lifted feet. Arrows indicate liftable feet. Central figure shows support polygon and location of vehicle center of pressure on terrain. Large box with central line is artificial horizon display of roll and pitch attitude.

expansion of the coordination computer. The former is needed to solve the problem of finding an appropriate distribution of foot forces among supporting legs of the ASV. While this computer is able at present to provide useable answers to this problem, calculation of optimal forces is likely to require an upgrade of this part of the on-board computer to a vector processor or some other type of special computing structure. Likewise, while the safety computer is adequate at present, in the long range, more computational power may be needed at this level due to the logical complexity and all-encompassing nature of this function. A small LISP machine is being considered for this purpose as part of a future ASV computer upgrade.

The logical level of control of the ASV is the hardest to understand and the least developed. At present, as can be seen from Fig. 12, the guidance computer consists of four Intel 86/30 boards assigned to individual functions as follows: terrain data conversion, terrain data storage, vehicle trajectory generation, and guidance coordination. The first of these functions refers to the need to convert scanner data from range measurements in vehicle polar coordinates to an elevation map in Earth-fixed Cartesian coordinates. As mentioned previously, a speed increase by a factor of sixteen is needed in this computer to allow the full data stream from the terrain scanner to be utilized in this process. The terrain data storage computer maintains the local terrain map in its associated 512 K byte memory, discarding old data and replacing it with new, as appropriate. The vehicle trajectory generation computer uses the terrain map to choose footholds and plan the body motion of the ASV, taking into account inputs from the operator's control stick. An important feature of this computation is that a "deceleration plan" capable of bringing the vehicle to a safe stop is always maintained. This plan over-rides the operator's commands when required. The guidance coordination computer coordinates the above functions and manages communications with the coordination computer. All of this software has been tested using a simulation of both terrain and vehicle kinematics on the PDP-11/70 computer. Laboratory testing and calibration of the optical radar system is under way at the time of this writing. Evidently, full evaluation of this level of software will require outdoor operation of the completed ASV system.

As can be seen on Fig. 16, the functions of the ASV guidance computer are paralleled by those of the human operator. As described in the discussion of operational modes in a preceding section of this report, in certain conditions the operator provides the only commands to the coordination computer, while in others his function is minimal. This matter is further discussed in the preceding discussion of operator's controls and displays. At present, the cockpit computer has been completely programmed for all functions currently provided for in the ASV cab instrumentation. Fig. 17 shows typical information provided to the operator by the ASV graphical display system during vehicle operation in precision footing mode.

The above discussion has been concerned only with the ASV application software. To assure proper functioning of this software in the ASV multiprocessor computer, substantial advances were also required in the area of system software. Like the application software, this system software has a somewhat generic quality, with a significance which goes beyond its immediate application to the ASV problem [43,47,48,51]. While this subject is extraordinarily complex, a brief history of the evolution of the ASV system software may serve to illuminate the nature of some of the problems and the solutions adopted for the vehicle on-board computer.

The ASV control software has its origins in earlier control programs for the OSU Hexapod [7,9,17,18,21]. Since these programs were all written in PASCAL for the PDP-11/70 computer running in time-shared mode under the RSX-11/M operating system, they were subject to the limitations of this computing environment. In particular, while multi-tasking is possible under RSX-11/M, and was used to a small degree in some OSU Hexapod software [18,21], most of the control programs for this machine were of the "big loop" variety [31] in which all calculations were performed serially at a rate sufficiently rapid to minimize the destabilizing effects of time sampling. As the magnitude of the ASV computing problem came to be understood, it became clear that a concurrent process model for its control software provided a more effective approach, especially in a multi-computer environment. As a first step in understanding this problem, the sequential software of the OSU Hexapod was decomposed into six parallel processes, each of which ran on one Intel 86/30 single-board computer. Each of these was connected to a common Intel Multibus. In addition, one of these computers, designated the cockpit computer, communicated in real time with a human operator and also with the PDP-11/70 computer. The latter computer simulated the vehicle and terrain and presented a vector graphics display of vehicle motion to the operator [43].

The above experiment provided several important results which affected the design and implementation of ASV system software. First of all, the Multibus system was found to be very lightly loaded. A consequence of this finding was that a multiple bus-master communication scheme is possible. That is, it was predicted from this study, and later verified by experimentation, that bus contention is not a serious problem for the multi-computer structure illustrated by Fig. 12. Of course, this is due not only to the hardware characteristics of the Multibus, but also results from a careful partitioning of control software to minimize the amount of communication required between the various computers in the system. A second finding of [43] was that PL/M is a suitable language for system programming. In particular, an operating system written in this language provides easy compatibility with application software written in PASCAL. The third point clarified by the research of [43] is that commands and data must be treated differently in the ASV application. Specifically, commands must be stored in a queue to be sure they are executed exactly once. In contrast, data should always represent the most recent information available, providing that all data words are consistent. That is care must be taken to ensure that a block of data has not been partially overwritten. This requirement is satisfied by a triple buffering scheme described in [43].

Subsequent research has led to a redesign and improvement of the system software developed in [43]. At present, the ASV on-board control computer executes approximately forty concurrent processes. Communication among these processes is achieved by software "mailboxes." Mailboxes permit communication between processes running on the same board or between processes on different boards with equal ease. A special type of mailbox called a "sticky mailbox" always contains the latest complete version of any data package [51]. This information can be read any number of times by any process until it is replaced by new information. Interference between reading and writing of a data packet is prevented by a semaphore system which is invisible to the user.

The above described features have been integrated into an operating system called GEM (Generalized Executive for real-time Multiprocessor applications) [51]. An important feature of GEM is that it has been designed to operate with a very low computational overhead and to make efficient use of Multibus communication facilities. At the present time, it is estimated that the bus utilization factor for the ASV control system running under GEM is less than 10 percent in precision footing mode. While it is anticipated that this number will not change significantly for other ASV control modes, this low utilization factor provides a substantial margin of safety relative to future expansion or modification of the currently envisaged operational modes.

4. SUMMARY

This three-year research program was aimed at the design and construction of a man-carrying six-legged walking vehicle embodying the highest possible degree of automation of vehicle leg motion coordination and energy distribution. By the end of the project, all design concepts had been validated and construction and testing of all major subsystems was completed. The final vehicle configuration achieves all initial design goals except for weight. Total vehicle weight is now estimated to be 6,000 lb. (including fuel, a human operator, and a 500 lb. payload), whereas the original project goal was aimed at about half this weight. The growth in weight over the original design goal is mainly the result of a deliberate decision to sacrifice this objective in order to maintain other more basic goals relating to vehicle speed, agility, load carrying capacity, safety, etc. These tradeoffs are discussed in detail in the body of this report.

The ASV machine represents the most technologically advanced off-road vehicle ever constructed. Its design required much basic research which was carried out in an accelerated manner and resulted in a total of 19 M.S. theses and 7 Ph.D. dissertations as well as numerous publications in the open literature. Thus, the ASV project produced not only a vehicle, but also added significantly to the available manpower pool and to the store of basic knowledge needed for further advances in the field of mobile robotic systems.

The ASV system described in this report is a proof-of-concept vehicle and not an operational prototype. However, based on experience gained in its design and construction, we believe that it would be possible to develop a more advanced system featuring greater agility, higher speed, reduced weight, and autonomous operation. The conceptual design of such a machine, called an

Agile Autonomous Vehicle (AAV), is the principal goal of our current research efforts under DARPA Contract No. DAAE07-84-K-R001. The ASV will serve as the primary experimental test bed for evaluation of AAV system concepts, component evaluation, and software development during the period August 1, 1984 through April 30, 1987. It is our hope that the outcome of this research will be sufficiently positive to justify the subsequent construction of an AAV system.

APPENDIX 1

LIST OF PUBLICATIONS

4/3/85

RESEARCH PUBLICATIONS SUPPORTED BY CONTRACT MDA903-82-K-0058

College of Engineering
The Ohio State University
Columbus, Ohio 43210

The following theses, dissertations, reports, and technical papers have een produced with the support of DARPA Contract MDA903-82-K-0058 since its nception on October 1, 1981. Copies of most of these documents are available pon request.

- Waldron, K.J., Song, S.M., Vohnout, V.J. and Kinzel, G.L., "Computer-Aided Design of a Leg for an Energy-Efficient Walking Machine," Proceedings of the 7th Applied Mechanisms Conference, Kansas City, December 7-9, 1981, pp. VIII-1 to VIII-8.

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